Guide to Thermal Properties of Concrete and Masonry Systems

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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 mass of concrete and masonry, passive solar design, and procedures to limit condensation within assemblages.

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

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CHAPTER 1—INTRODUCTION

1.0—Introduction

The recurrence of energy crises, coupled with increased public awareness and government action, have encouraged the development of building codes that include energy-conservation requirements. To reduce the use of nonrecoverable energy sources, almost all states and authorities have now adopted energy-conservation building codes and standards that apply to the design and construction of buildings. The design of energy-conserving buildings now 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 for 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 concrete and masonry buildings.

1.1—Energy conservation with concrete and masonry

Due to its inherent functionality and the availability of raw materials used in its 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 produced acceptable interior temperatures despite high outside temperatures.

Housing systems have been developed featuring efficient load-bearing concrete masonry wall systems that provide resistance to weather, temperature changes, fire, and noise. Many of these wall systems are made with lightweight concrete where the wall thickness is often determined by thermal characteristics rather than structural requirements.

Numerous organizations (National Institute of Standards and Technology; American Society of Heating, Refrigeration and Air-Conditioning Engineers; National Concrete Masonry Association; and Portland Cement Association) 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. 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). More sophisticated calculations are required to account for the dynamic, real-world performance of concrete and concrete masonry walls.

1.2—Building enclosure requirements

In addition to structural requirements, a building envelope should be designed to control the flow of air, heat, sunlight, radiant energy, and water vapor, and to limit the entry of rain and snow. It should also provide the many other attributes generally associated with enclosure materials, including fire and noise control, structural adequacy, durability, aesthetic quality, and economy. Any analysis of building enclosure materials should extend beyond heat-flow analysis to also account for their multifunctional purpose. The non-heatflow 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—THERMAL CONDUCTIVITY OF CONCRETE, AGGREGATE, AND CEMENT PASTE

2.0—Introduction

Thermal conductivity is a specific property of a gas, liquid, or solid. The coefficient of thermal conductivity k is a measure of the rate at which heat (energy) passes perpendicularly through a unit area of homogeneous material of unit thickness for a temperature difference of one degree; k is expressed as Btu · in./(h · ft^2 · °F)[W/(m^{2}K)].

The thermal resistance of a layer of material can be calculated as the thickness of the layer divided by the thermal conductivity of the material. If a wall is made up of uniform layers of different materials in contact with each other, or separated by continuous air spaces of uniform thickness, the resistances of each layer are combined by a simple addition. Surface-air-film resistances should be included to yield the wall's total thermal resistance (*R*-value). If any air spaces are present between layers, the thermal resistances of these air spaces are also included.

2.1—Thermal conductivity of concrete

The thermal conductivity of a material, such as concrete or insulation, is usually determined by measuring in accordance with ASTM C 177 or ASTM C 236. Results of many such measurements have been tabulated in the *ASHRAE* (American Society of Heating, Refrigeration and Air-Conditioning Engineers) Handbook of Fundamentals. Several methods for calculating concrete thermal conductivity have been developed and will be discussed here. These calculated estimates are useful if test data are not available.

Basic testing programs conducted by the former National Bureau of Standards (now the National Institute of Standards and Technology), the U.S. Bureau of Reclamation, and the University of Minnesota 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 d (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

$$k_c = 0.5e^{0.02d} \text{ (inch-pound units)} \quad (2\text{-}1)$$

$$k_c = 0.072\, e^{0.00125d} \text{ (S.I. units)}$$

where d = oven-dry density in lb/ft^3 [kg/m^3].

Thermal conductivity values for concretes with the same density made with different aggregates can differ from the relationship expressed by Eq. (2-1) and may underestimate k_c for normalweight concretes and for lightweight concretes

Table 2.1—Thermal conductivity of oven-dry lightweight concrete, mortar, and brick*

Thermal conductivity, Btu/h · ft^2 · (°F/in.), at oven-dry density in lb/ft^3†

Material, type of aggregate in concrete or data source	Density															
	15	20	25	30	40	50	60	70	80	90	100	110	120	130	140	150
Equation (2-1) $k_c = 0.05e^{0.02d}$	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
1985 ASHRAE Chapter 23	—	0.7	—	0.9	1.15	—	1.7	—	2.5	—	3.6	—	5.2	—	9.0	—
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	—	—	—	—	—	—	1.71	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	2.32	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.
†Multiply Btu/h · ft^2 · (°F/in.) values by 0.1442 to convert to W/m · K. Multiply lb/ft^3 values by 16 to convert to kg/m^3.

Table 2.2—Thermal conductivity moisture correction factors*

Material or type of aggregate in concrete	Type of exposure	Relative humidity mean, %	Moisture content, % by weight	Thermal conductivity moisture correction factor, % increase in thermal conductivity per 1% 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 Uh‡	80 80	5.5 7.0	4.25 4.25	1.22 1.30
Sintered fly ash, scoria, and coal cinders	Pr Uh	60 80	3.75 5.0	6.0 6.0	1.22 1.30
Expanded slag	Pr Uh	80 80	3.5 5.5	5.5 5.5	1.20 1.30
Expanded and sintered clay, shale, slate (no natural sand); sanded expanded slag	Pr Uh	80 80	3.5 5.5	4.0 4.0	1.14 1.22
Sanded expanded and sintered clay, shale, and slate	Pr Uh	60 80	3.0 5.0	5.0 5.0	1.15 1.25
Limestone	Pr Uh	60 80	2.0 3.0	7.0 7.0	1.15 1.22
Sand gravel, < 50% quartz or quartzite	Pr Uh	60 80	2.0 3.0	7.0 7.0	1.15 1.22
Sand gravel, > 50% quartz or quartzite	Pr Uh	60 80	2.0 3.0	9.0 9.0	1.18 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 Uh	60 80	0.5 2.0	30.0 20.0	1.15 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.
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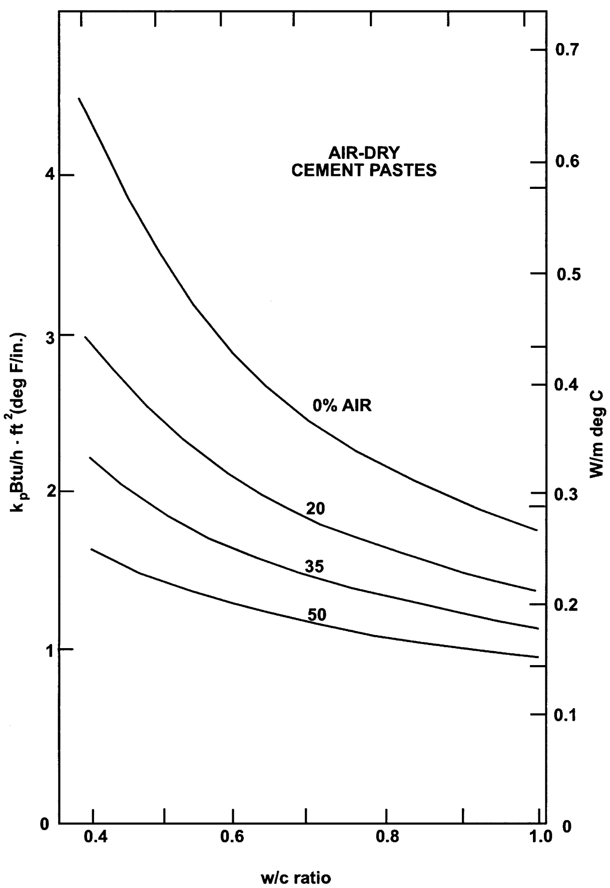

Fig. 2.1—Thermal conductivity k_p *for air-dry-hardened portland cement pastes.*

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. (2-1) for concretes with densities from 20 lb/ft^3 to 100 lb/ft^3 [320 to 1600 kg/m^3] correlate better to test data than for concretes outside this density range (Valore 1980). Oven-dry thermal-conductivity values for several aggregates, concretes made with various aggregates, mortar, and brick are shown in Table 2.1. 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).

2.2—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 2.2 lists multipliers used to correct oven-dry-concrete thermal conductivities to practical design values. Data in Table 2.2 can be used to estimate k_c values for in-service concrete and concrete masonry walls.

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

$$k_c(\text{corrected}) = k_c\left[1 + \frac{(6d_m - d_o)}{d_o}\right] \quad (2\text{-}2)$$

Table 2.3—Thermal conductivity of some natural minerals

Mineral	Thermal conductivity	
	Btu/hr · ft^2 (°F/in.)	*W/m*, °C
Quartz (single crystal)	87, 47	12.5, 6.8
Quartz	40	5.8
Quartzite	22 to 37	3.2 to 5.3
Hornblende-quartz-gneiss	20	2.9
Quartz-monzonite	18	2.6
Sandstone	9 to 16	1.3 to 2.3
Granite	13 to 28	1.9 to 4
Marble	14 to 21	2 to 6
Limestone	6 to 22	1 to 3
Chalk	6	0.9
Diorite (dolerite)	15.6	2.25
Basalt (trap rock)	9.6 to 15	1.4 to 2.2
Slate	13.6	2

Note: Reprinted from "Calculation of U-Values of Hollow Concrete Masonry," R. C. Valore, Jr., *Concrete International*, V. 2, No. 2, Feb. 1980.

where d_m and d_o are densities of concrete in moist and oven-dry conditions, respectively.

For most concrete walls, a single factor of 1.2 can be applied to oven-dry k_c values (Valore 1980). It then becomes necessary only to change the constant in Eq. (2-1) from 0.5 [0.072] to 0.6 [0.0865] to provide for a 20% increase in k_c for air-dry, in-service, concrete, or concrete masonry:

$$k_c = 0.6 \cdot e^{0.02d} \text{ (inch-pound units)} \quad (2\text{-}3)$$

$$k_c = 0.0865 \cdot e^{0.00125d} \text{ (S.I. units)}$$

2.3—Thermal conductivity of aggregates and cement paste

Table 2.3 lists conductivity values for some natural minerals used as concrete aggregates. Figure 2.1 shows calculated thermal conductivity values for air-dry, hardened cement pastes k_p (Valore 1980). These values are in good agreement with experimental values determined by Spooner (Tyner 1946; Spooner 1977) for pastes with five water-cement ratios (*w/c*) ranging from 0.47 to 0.95. Experimental values averaged approximately 5% lower than calculated values for pastes with *w/c* in the range of 0.47 to 0.95, and 16% lower for paste with 0.35 *w/c*. Lentz and Monfore (1965b) showed that conductivity k_p for mature pastes in a moist-cured condition with *w/c* ratios of 0.4, 0.5, and 0.6 agreed within 2% of those calculated by Eq. (2-1) when corrected to an oven-dry condition. The value for a 0.32 *w/c* paste, however, differed from the Eq. (2-1) value by approximately 20%.

2.4—Thermal conductivity of concrete used in concrete masonry units

Concrete Masonry Units (CMU) usually consist of approximately 65 to 70% aggregate by volume. The remaining volume consists of voids between aggregate particles, entrained air, and cement paste. The typical air-void content of concrete used to make lightweight CMUs, for example, has been found to be 10 to 15% by volume. Expressed as a percentage of the cement paste, void volumes are approximately 30 to 45%. For a typical lightweight CMU having a net *w/c* of 0.6

and an average cement-paste air-void content of 40%, the thermal conductivity would be in the range of 1.5 to 1.8 Btu · in./h · ft^2 · °F [0.22 to 0.26 W/(m^{2}K)]. Such values are considerably lower than those in Eq. (2-1) or Eq. (2-2) for typical lightweight aggregate, concrete (void-free) (Valore 1980) because the air spaces found in the zero slump CMU lightweight concrete provide additional heat flow resistance, thus lowering the conductivity.

2.5—Thermal conductivity of two-phase systems

The cubic model (Valore 1980) described in Section 2.6 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. 2.2). For lightweight-aggregate concretes, Eq. (2-1) yields k_c values similar to those determined by using the cubic-model equation, Eq. (2-4). Equation (2-1) is not always accurate over a wide range of concrete densities (Valore 1980), particularly above 100 lb/ft^3 [1600 kg/m^3], because aggregate mineralogical characteristics cause a wide range of aggregate thermal conductivities. The cubic-model equation is also appropriate for calculating thermal conductivities of concretes above 100 lb/ft^3 [1600 kg/m^3]. 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. (This insulative effect of the cement paste matrix on k_c is determined by its quantity and quality, that is, the paste volume fraction and density.) The cubic model also explains how normal-weight aggregates produce disproportionately high conductivity values when added to lightweight-aggregate concrete.

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

2.6—Sample thermal conductivity calculations using the cubic model

The cubic model can be used to calculate k_c as a function of cement paste conductivity, aggregate conductivity, and aggregate volume. The cubic model (Fig. 2.2) 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 relatively low conductive materials that greatly increase the composite system's conductivity. In the case of concrete, highly conductive aggregates are the thermal bridges and they are surrounded by the lower conductive cement paste and/or and fine aggregate matrix. To use the cubic model, Eq. (2-4), 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.

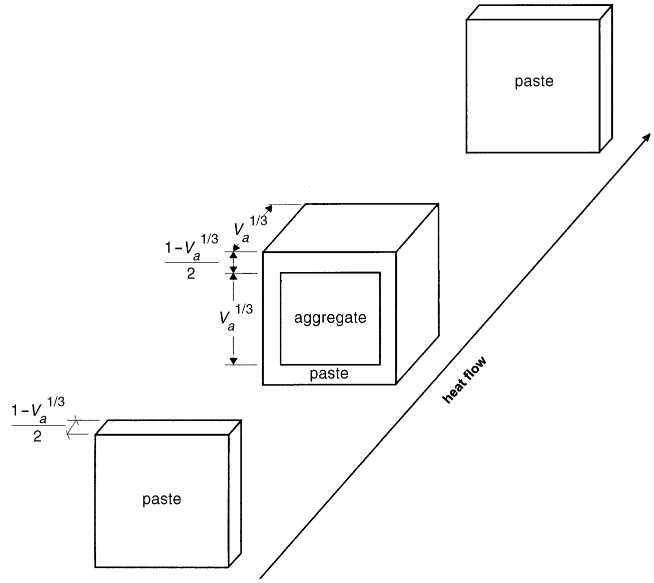

Fig. 2.2—Cubic model for calculating thermal conductivity k_c *of concrete by Valore as a function of conductives* k_p *and* k_a *of cement paste and aggregate, and volume fraction* V_a *of aggregate.*

$$k_c = k_p\left[\frac{V_a^{2/3}}{V_a^{2/3} - V_a + \left(\frac{V_a}{\left(\frac{k_a V_a^{2/3}}{k_p}\right) + 1 - V_a^{2/3}}\right)}\right] \quad (2\text{-}4)$$

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/ft^3 [1920 kg/m^3] or less, thermal conductivities determined using Eq. (2-4) show good agreement with the thermal conductivity determined using the simpler conductivity/density relationship of Eq. (2-1). For normalweight concretes with densities greater than 120 lb/ft^3 [1920 kg/m^3], Eq. (2-4) yields more accurate k_c values than Eq. (2-1).

2.7—Practical thermal conductivity

Practical thermal conductivity design values for normal-weight and lightweight concrete, solid clay brick, cement mortar, and gypsum materials are suggested in Table 2.4 (Valore 1988).

CHAPTER 3—CALCULATION METHODS FOR STEADY-STATE THERMAL RESISTANCE OF WALL SYSTEMS

3.0—Introduction

Thermal resistance, or *R*-value as it is commonly known, is the most widely used and recognized thermal property. Building codes generally prescribe requirements for minimum *R*-value or maximum thermal transmittance, *U*-value, for

Table 2.4—Suggested practical thermal conductivity design values[*]

Practical thermal conductivity in Btu/h · ft² · (°F/in.) at oven-dry density in lb/ft³[†]

Group	Material or type of aggregate of concrete	Exposure type[‡]	Density 15	20	25	30	40	50	60	70	80	90	100	110	120	130	140	150
Matrix insul.	Neat cement paste and foam concrete	Pr	0.7	0.8	0.9	1.1	1.4	1.7	2.1	2.5	3.0	3.5	4.1	4.7	5.4	—	—	—
Insul., struct.	Autoclaved aerated (cellular)	Pr	0.6	0.7	0.8	1.0	1.3	1.6	2.0	2.5	—	—	—	—	—	—	—	—
Insul.	Expanded polystyrene beads, perlite, vermiculite, expand, glass	Pr	0.65	0.8	0.95	1.1	1.5	1.9	2.4	—	—	—	—	—	—	—	—	—
Blocks, struct.	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	—	—	—
Blocks, struct.	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	—	—	—	—
Blocks, struct.	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			
Blocks, struct.	Limestone	Pr	—	—	—	—	—	—	—	—	—	—	5.5	6.6	7.9	9.4	11.1	13.8
		Un	—	—	—	—	—	—	—	—	—	—	5.85	7.0	8.3	10.0	11.7	13.75
Blocks, struct.	Sand gravel, < 50% quartz or quartzite	Pr	—	—	—	—	—	—	—	—	—	—	—	—	—	10.0	13.8	18.5
		Un	—	—	—	—	—	—	—	—	—	—	—	—	—	10.7	14.6	19.6
Blocks, struct.	Sand gravel, > 50% quartz or quartzite	Pr	—	—	—	—	—	—	—	—	—	—	—	—	—	11.0	15.3	20.5
		Un	—	—	—	—	—	—	—	—	—	—	—	—	—	11.8	16.5	22.0
Insul. struct. masonry	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.
[†]Multiply Btu/h · ft² · (°F/in.) values by 0.1442 to convert to W/m · K; multiply lb/ft³ values by 16.03 to convert to kg/m³.
[‡]Pr = protected exposure; mean relative humidity in wall up to 60%. 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%. Exterior wall surface uncoated or treated with a water repellent or clear sealer only.
[§]Densities above 100 lb/ft³ do not apply to pumice or expanded clay or shale concretes.
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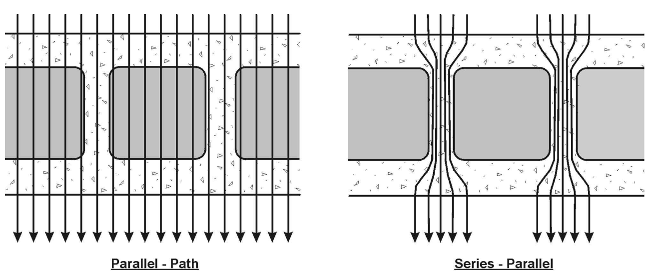


Fig. 3.1—Parallel and series parallel heat flow schematics.

elements of a building envelope. Thermal resistance R is the reciprocal of thermal conductance $1/C$ and does not include surface-air-film resistances. Thermal conductance C is the coefficient of heat transfer for a wall and does not include surface-air-film resistances. Thermal transmittance U is the overall coefficient of heat transfer and does include the interior and exterior surface-air-film resistances plus the wall's thermal resistance. The total thermal resistance of a wall (R_T) is the reciprocal of U; $R_T = 1/U$ h · ft² · °F/Btu [m²K/W]. Units for U-value and C are Btu/h · ft² · °F [W/(m²K)].

3.1—Thermal resistance of concrete masonry units

Thermal resistance of CMUs is affected by many variables, including unit shape and size, concrete density, insulation types, aggregate type(s), aggregate gradation, aggregate mineralogy, cementitious binder, and moisture content. It simply is not feasible to test all of the possible variations. More than 100 CMU walls, however, have been tested (Tables 3.1 and 3.2) (Valore 1980). These tests provide a basis for comparison of various calculation methods. Two calculation methods have been widely used and accepted: the parallel-path method and the series-parallel method (also known as isothermal planes). Both methods are described in Section 3.2.

3.2—Methods for calculating thermal resistance of concrete masonry units

The parallel-path method was considered acceptable practice until insulated CMUs appeared in the marketplace. The parallel-path method assumes that heat flows in straight parallel lines through a CMU. If a hollow CMU has 20% web area and 80% core area, this method assumes that 20% of the heat flow occurs through the web and 80% occurs through the core (Fig. 3.1). This method is reasonably accurate for uninsulated hollow CMUs.

The series-parallel (also known as isothermal planes) method is the current practice and provides good agreement with test data for both uninsulated and insulated CMUs. As with fluid flow and electrical currents, the series-parallel method considers that heat flow follows the path of least resistance. It accounts for lateral heat flows in CMU face shells and heat bypassing areas of relatively high thermal resistance, either air space or insulation in the hollow cores. Therefore CMU cross webs are a thermal bridge. As shown in Fig. 3.1, heat flow is mostly concentrated in webs.

The basic equation for the series-parallel method is

Table 3.1—Calculated and ASTM C 236 *U*-values for concrete block walls with cores empty and filled

Wall no.	Number of cores	Block dimensions: L_b*, in.	Block dimensions: fs, in.	Fractional web face area: a_w	Aggregate	Concrete: d, lb/ft³*	Concrete: k_c	Core fill: Type	Core fill: k_f	*U*-value, Btu · (h · ft² · °F)*, Cores empty, Calculation method 1	Cores empty, Calculation method 2	Cores empty, Test	Cores filled, Calculation method 1	Cores filled, Calculation method 2	Cores filled, Test
PS-1	2	5.625	2.38	0.22	LW	85	3.28	Perl.	0.45	0.391	0.395	0.36	0.174	0.212	0.20
PS-2	2	7.625	3.04	0.22	LW	82	3.09	Perl.	0.45	0.344	0.347	0.33	0.131	0.159	0.15
PS-3	2	11.625	3.46	0.27	LW	80	2.97	Perl.	0.45	0.301	0.314	0.29	0.093	0.108	0.10
PS-4	2	7.625	3.04	0.22	Ex. slag	90	2.90	Perl.	0.45	—	—	—	0.128	0.153	0.152
PS-5	2	11.625	3.46	0.27	Ex. slag	90	2.90	Perl.	0.45	—	—	—	0.092	0.107	0.113
PS-6	2	7.625	3.04	0.22	Limestone	138	9.48	Perl.	0.45	—	—	—	0.201	0.326	0.341
PS-7	2	11.625	3.46	0.27	Limestone	139	9.48	Perl.	0.45	—	—	—	0.167	0.246	0.221
PS-8	3	5.625	2.38	0.29	LW	87	3.42	Verm.	0.60	0.398	0.399	0.40	0.218	0.261	0.26
PS-9	2	7.625	3.04	0.22	LW	85	3.28	Verm.	0.60	0.353	0.355	0.33	0.152	0.178	0.17
PS-10	3	11.625	3.46	0.36	LW	82	3.09	Verm.	0.60	0.296	0.310	0.30	0.119	0.135	0.15
PS-11	2	7.625	3.04	0.22	LW	126	7.46	Verm.	0.60	0.468	0.472	0.53	0.20	0.291	0.36
PS-12	3	3.625	2.36	0.29	Ex. shale	76	2.74	Ex. shale	1.2	0.398	0.409	0.43	0.390	0.403	0.42
PS-13	2	7.625	3.04	0.22	Ex. shale	77	2.80	Ex. shale	1.2	0.330	0.333	0.30	0.197	0.204	0.21
PS-14	2	11.625	3.46	0.27	Ex. shale	71	2.48	Ex. shale	1.2	0.275	0.290	0.30	0.129	0.133	0.16
PCA-1	3	7.625	3.00	0.38	Ex. shale	84	3.22	Ex. shale	1.2	0.343	0.346	0.36	0.228	0.242	0.24
PCA-2	3	7.625	3.00	0.38	Ex. shale	84	3.22	Verm.	0.60	0.343	0.346	0.34	0.183	0.214	0.21
PCA-3	3	7.625	3.00	0.38	Sand-LW	97	4.18	Verm.	0.60	0.386	0.387	0.39	0.209	0.251	0.24
PCA-4	3	7.625	3.00	0.38	Sand-grav.	136	9.11	Verm.	0.60	0.514	0.527	0.55	0.296	0.421	0.45
UM-1b,c	3	7.88	3.17	0.32	Cinders	86	3.35	Cork	0.35	0.346	0.348	0.370	0.144	0.185	0.201
UM-1d	3	7.88	3.17	0.32	Cinders	86	3.35	Cind.	2.0	0.346	0.348	0.370	0.264	0.268	0.248
UM-1e	3	7.88	3.17	0.32	Cinders	86	3.35	Rock wool	0.35	0.346	0.348	0.370	0.144	0.185	0.211
UM-2b,c	3	7.88	3.17	0.32	Ex. shale	77	2.80	Cork	0.35	0.318	0.322	0.344	0.131	0.163	0.172
UM-3b,c	3	7.88	3.17	0.32	Sand-grav.	126	7.46	Cork	0.35	0.471	0.476	0.509	0.214	0.325	0.379
UM-4a	3	7.88	3.17	0.32	Limestone	134	8.75	—	—	0.949	0.504	0.510	—	—	—
UM-5a,b	3	11.88	3.71	0.37	Cinders	86	3.35	Cork	0.35	0.299	0.312	0.374	0.109	0.132	0.199
UM-6a	3	11.84	3.71	0.37	Sand-grav.	125	7.31	—	—	0.420	0.421	0.481	—	—	—
UM-7a	3	4.17	2.02	0.34	Cinders	100	4.43	—	—	0.489	0.493	0.599	—	—	—
UM-8a†	3	4.17+	2.02	0.34	Cinders	100	4.43	Rock	0.35	0.233	0.239	0.279	0.162	0.165‡	0.176
UM-8b§	—	4.17	—	—	—	—	—	Wool	—	—	—	—	—	—	—
UM-9b‖	2	7.78	2.06	0.39	Sand-grav.	135	8.93	—	—	0.515	0.520	0.525	—	—	—
UM-10a	3	6.00	2.10	0.37	Cinders	74	2.64	—	—	0.366	0.368	0.424	—	—	—
UM-11a	3	7.85	3.17	0.32	A. C. slag	126	5.97	—	—	0.437	0.438	0.441	—	—	—
UM-15a,b	3	11.75	3.17	0.37	Ex. shale	77	2.80	Cork	0.35	0.274	0.289	0.342	0.096	0.114	0.148
NW-1	2	7.62	3.80	0.22	Pumice	72	2.53	Perl.	0.45	0.292	0.294	0.25	0.129	0.152	0.13

*Multiply Btu/h · ft² · °F values by 5.68 to convert W/m²K; multiply lb/ft³ values by 16 to convert to kg/m³; multiply in. values by 25.4 to convert to mm.
†Cavity wall with 1 in. air space.
‡U-value is 0.171 when corrected for metal ties by Method 2.
§Cavity filled with rock wool.
‖Nominal size of unit 8 x 5 x 12 in. (200 x 125 x 300 mm).
Note: C 236 test data from: 1) Pennsylvania State University (private communication with F. Erskine, furnishing reports of ASTM C 236 tests of walls performed by Pennsylvania State Laboratories University); 2) Portland Cement Association (Brewer, H. W., "Thermal Properties of Concrete Wall Constructions, Steady-State Hot-Box Method," unpublished report No. 1407, Research and Development Laboratories, Portland Cement Association, Jan. 1969; 3) University of Minnesota (Rowley and Algren); and 4) Northwest Laboratories (private communication with L. Santo, furnishing a report of ASTM C 236 test of walls performed by Northwest of Portland, Oreg.)
Note: U.S. units.
Reprinted from "Calculation of U-*Values of Hollow Concrete Masonry," R. C. Valore, Jr.,* Concrete International*, V. 2, No. 2, Feb. 1980.*

$$R_T = R_f + \frac{1}{\left(\frac{a_{np}}{R_{np}} + \frac{a_{np}}{R_{np}}\right)} + \ldots + \frac{1}{\left(\frac{a_{np}}{R_{np}} + \frac{a_{np}}{R_{np}}\right)} \qquad (3\text{-}1)$$

where

a_{np} = fractional area of heat flow path number p of thermal layer number n;

R_{np} = thermal resistance of heat flow path number p of thermal layer number n, h · ft² · °F/Btu (m²K/W);

R_f = surface-air-film resistances, equal to 0.85 h · ft² · °F/Btu (0.149 m²K/W); and

R_T = total CMU thermal resistance including surface-air-film resistance, h · ft² · °F/Btu (m²K/W).

Using this method, the masonry unit is divided into thermal layers. Thermal layers occur at all changes in unit geometry and at all interfaces between adjacent materials. For example, a hollow uninsulated CMU will have three thermal layers:

1. The interior face shell and mortar joint;
2. The hollow core air space and cross web; and

Table 3.2—Calculated and ASTM C 236 *U*-values for concrete block walls with cores empty and filled

Wall no.	Number of cores	Block dimensions		Fractional web face area	Aggregate	Concrete		Core fill		U-value, Btu · (h · ft^2 · °F)*					
										Cores empty			Cores filled		
										Calculation method			Calculation method		
		L_b*, in.	fs, in.	a_w		d, lb/ft^3*	k_c	Type	k_f	1	2	Test	1	2	Test
D-2	2	5.625	2.38	0.22	Sand-grav.	131	8.31	—	—	0.514	0.535	0.58	—	—	—
D-4	2	7.625	3.04	0.22	Sand-grav.	132	8.41	—	—	0.483	0.490	0.56	—	—	—
D-4	2	11.625	3.46	0.27	Sand-grav.	135	8.93	—	—	0.456	0.456	0.48	—	—	—
D-7	2	7.625	3.04	0.22	Pumice	62	2.07	—	—	0.286	0.292	0.33	—	—	—
D-10	2	11.625	3.46	0.27	Sand-LW	95	4.01	—	—	0.347	0.354	0.35	—	—	—
D-11	2	7.625	3.04	0.22	Sand-LW	95	4.01	—	—	0.383	0.383	0.42	—	—	—
D-21	2	7.625	3.04	0.22	Fly ash	80	2.97	—	—	0.339	0.341	0.36	—	—	—
D-38†	2	7.625	3.04	0.22	Fly ash	80	2.97	—	—	0.333	0.335	0.33	—	—	—
D-24,25	3	5.625	2.38	0.29	Sand-LW	98	4.26	Perl.	0.45	0.432	0.433	0.42	0.216	0.286	0.30
D-UF1‡	2	7.625	3.04	0.22	Sand-LW	105	4.90	Urea-foam.	0.30	—	—	—	0.138	0.201	0.24
D-UF2‡	2	7.625	3.04	0.22	Sand-grav.	133	8.58	Urea-foam.	0.30	—	—	—	0.174	0.297	0.30
D-UF3‡	2	11.625	3.46	0.27	Sand-LW	113	5.75	Urea-foam.	0.30	—	—	—	0.119	0.165	0.18
D-UF4‡	2	11.625	3.46	0.27	Sand-grav.	133	8.58	Urea-foam.	0.30	—	—	—	0.148	0.224	0.23
D-UF5‡	2	11.625	3.46	0.27	LW	91	3.70	Urea-foam.	0.30	—	—	—	0.093	0.118	0.12
RI-1	2	7.625	3.04	0.22	Sand-grav.	140	9.87	—	—	0.503	0.517	0.508	—	—	—
RI-2	2	7.625	3.04	0.22	LW	101	4.52	—	—	0.400	0.400	0.381	—	—	—

*Multiply Btu/h · ft^2 · °F values by 5.68 to convert W/m^{2}K; multiply lb/ft^3 values by 16 to convert to kg/m^3; multiply in. values by 25.4 to convert to mm.
†Fibered surface-bonded cement plaster on both sides.
‡Urea-formaldehyde insulation foamed in place at cores.
Note: C 236 test data from: 1) Private communication with T. Redmond furnishing reports of ASTM C 236 tests of walls by Dynatech R/D Co.; and 2) University of Rhode Island (Private communication with J. F. Boux, General Concrete of Canada, Limited, furnishing reports of ASTM C 236 tests of walls with urea-formaldehyde core insulation [tests were performed by Dyanatech R/D Co.]).
Note: U.S. units.
Reprinted from "Calculation of U-*Values of Hollow Concrete Masonry," R. C. Valore, Jr.,* Concrete International*, V. 2, No. 2, Feb. 1980 (Table 10).*

Table 3.3—Dimensions of plain-end two-core concrete blocks, in inches (meters) for calculating *U*-values

Thickness		Actual length	Average face shell thickness x2	Average web thickness x3	Fractional web face area	Fractional core face area	Average core thickness or web length*
Nominal	Actual						
	L_b	A	fs	w	a_w (w/A)	a_c $(1 - a_w)$	L_f or L_w $(L_b - fs)$
4 (0.10)	3.625 (0.092)	15.625 (0.397)	2.36 (0.06)	3.42 (0.087)	0.22	0.78	1.265 (0.032)
6 (0.15)	5.625 (0.143)	15.625 (0.397)	2.38 (0.06)	3.45 (0.088)	0.22	0.78	3.245 (0.082)
8 (0.20)	7.625 (0.194)	15.625 (0.397)	3.04 (0.078)	3.48 (0.088)	0.22	0.78	4.585 (0.116)
10 (0.25)	9.625 (0.244)	15.625 (0.397)	3.46 (0.088)	3.81 (0.097)	0.24	0.76	6.165 (0.157)
12 (0.30)	11.625 (0.295)	15.625 (0.397)	3.46 (0.088)	4.17 (0.106)	0.27	0.73	8.165 (0.207)

*In direction of heat flow for Method 2 only; for Methods 1 and 3, web length is direction of heat flow in actual thickness L_b.
Reprinted from "Calculation of U-*Values of Hollow Concrete Masonry," R. C. Valore, Jr.,* Concrete International*, V. 2, No. 2, Feb. 1980.*

3. The exterior face shell and mortar joint.

A hollow CMU with an insulation insert placed over reduced cross webs in the middle of the CMU has five thermal layers:

1. The exterior face shell and mortar joint;
2. The full height concrete webs and hollow core air space;
3. The reduced height concrete webs combined with the insulating insert and air space;
4. The same as layer 2; and
5. The same as layer 1.

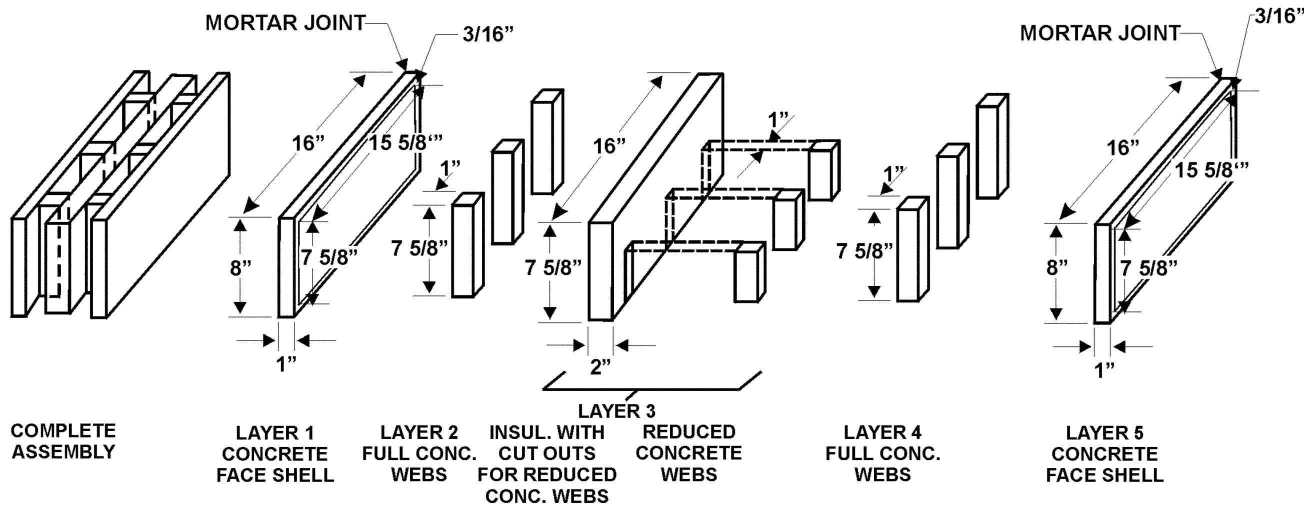
These five layers are shown in Fig. 3.2.

The series-parallel method also dictates that thermal layers be further divided into heat flow paths corresponding to the materials in each layer: for example, the reduced-cross-web insulated CMU. Layer one has two heat flow paths: the face shell concrete and the mortar joint mortar. Layer three has three heat flow paths: the reduced cross web concrete, the insulating insert insulation, and the air space. As is the case in most commercially available insulated CMUs, the insulating insert does not completely wrap the unit's webs (that is, it does not cover the mortar joint area and it does not have a 8 x 16 in. [200 x 400 mm] profile to fully cover a typical CMU's area) and that is why layer three must have three heat flow paths. If the insulating insert does in fact have an 8 x 16 in. [200 x 400 mm] profile, then the layer has only two heat flow paths: the reduced cross web and the insulating insert. Table 3.3 lists standard CMU dimensions.

3.3—Thermal resistance of other concrete wall systems

The series-parallel method can also be used to calculate the thermal resistance of other concrete wall systems, such as tilt-up walls, precast walls, insulated sandwich panels, and cast-in-place walls. Wall-shear connectors and solid-concrete perimeters in sandwich panels can have relatively high thermal conductivities and will act as thermal bridges in the same

Coefficients of Heat Transfer



EXAMPLE PROGRAM DATA

NAME: John Doe

DATE: November 2, 1999 **REF:** ACI Example

Description of Wall System: Integrally insulated CMU with reduced webs.

INPUT DATA

LAYER No.	LAYER THICKNESS (in.)	PATH No.	PATH HEIGHT (in.)	PATH WIDTH (in.)	PATH AREA (in.)	MATERIAL TYPE	MATERIAL RESISTIVITY (hr x sf x F/Btu x in)
1	1	1	7.625	15.625	119.141	CONCRETE	0.271
		2			8.859	MORTAR	0.20
2	2	1	7.625	1.0	22.875	CONCRETE	0.271
		2			105.125	AIR	0.97(2/6)=0.32
3	2	1	4.0	1.0	12.0	CONCRETE	0.271
		2	7.625	16.0	110.0	RIGID INSULATION	5.00
		3	0.375	16.0	6	AIR	0.32
4	2	1	7.625		22.875	CONCRETE	0.271
		2			105.125	AIR	0.32
5	1	1	7.625	15.625	119.141	CONCRETE	0.271
		2			8.959	MORTAR	0.20

Fig. 3.2—Five layers of an insulated hollow CMU.

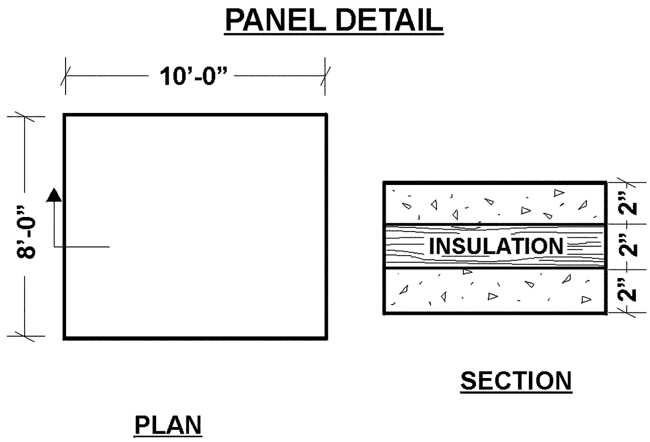


Fig. 3.3—Case I, no steel ties.

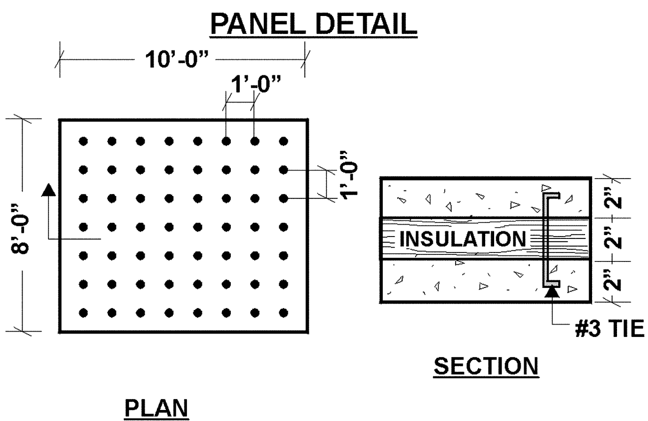


Fig. 3.4—Case II, steel ties.

manner as webs do in CMUs. When these wall types do not contain thermal bridges, the series-parallel equation can be simplified to a series equation that is, adding the resistances of each layer because each layer has only one path.

3.3.1 *Sample calculations*—The following three examples were developed by McCall (1985). Although Eq. (3-2) and (3-3) look different from Eq. (3-1), the basic principals of series-parallel heat flow are represented.

Case I—No steel ties

A sandwich panel is illustrated in Fig. 3.3 with a 2 in. (50 mm) concrete inner wythe, 2 in. (50 mm) extruded polystyrene insulation, and a 2 in. (50 mm) concrete outer wythe with no steel ties penetrating the insulation. The concrete has a density of 150 lb/ft^3 [2400 kg/m^3]. To calculate the U-value of this panel, add the individual thermal resistances of the inside surface air film, the inner wythe of concrete, the insulation, the outer wythe of concrete, and the outside surface air film and then take the reciprocal of this sum. The U-value of this panel is 0.09 Btu/h · ft^2 · °F [0.51 W/m^{2}K]. The results are illustrated in Table 3.4.

Case II—Steel ties

In comparison, consider a sandwich panel that has the same characteristics as the previous example except that it has No. 3 bars penetrating the insulation and 1 in. (25 mm) of concrete in each wythe as illustrated in Fig. 3.4.

To calculate the thermal resistance of the insulating layer, use the formula

Table 3.4—Thermal properties of sandwich panels with no shear ties

Panel components	Thermal resistance,* (°F · h · ft^2/Btu)
Inside air film	0.68
Inner wythe	0.17
Insulation	10.00
Outer wythe	0.17
Outer air film (15 mph [6.7 m/s] wind)	0.17
Total thermal resistance	11.19
U-value = 1/11.19 = 0.09 Btu/h · ft^2 · °F	

*Multiply °F · h · ft^2/Btu values by 0.176 to convert to m^{2}K/W.
Reprinted from "Thermal Properties of Sandwich Panels," W. Calvin McCall, Concrete International, *V. 5, No. 1, Jan. 1985.*

Table 3.5—Thermal properties of sandwich panel with No. 3 (No. 10) bar shear ties

Panel components	Thermal resistance,* (°F · h · ft^2/Btu)
Inside air film	0.68
Inner wythe	0.08
Insulation + 2 in. (50 mm) of concrete	6.26
Outer wythe	0.08
Outside air film	0.17
Total thermal resistance	7.27
U-value = 1/7.27 = 0.14 Btu/h · ft^2 · °F	

*Multiply °F · h · ft^2/Btu values by 0.176 to convert to m^{2}K/W.
Reprinted from "Thermal Properties of Sandwich Panels," W. Calvin McCall, Concrete International, *V. 5, No. 1, Jan. 1985.*

$$R_t = \frac{R_i R_s}{A_i R_s + A_s R_i} \tag{3-2}$$

where

R_i = resistance of insulation plus 2 in. (50 mm) of concrete, 10.17 h · ft^2 · °F/Btu (1.79 m^{2}K/W);
A_i = percentage of area occupied by insulation, 99.92%;
R_s = resistance of steel, 0.013 h · ft^2 · °F/Btu [0.0023 m^{2}K/W];
A_s = percentage of area occupied by steel, 0.08%; and
R_t = thermal resistance of the insulating layer.

The thermal resistance of the insulating layer is 6.26 h · ft^2 · °F/Btu [1.10 m^{2}K/W]. When compared to the previous example, it shows that if steel occupies 0.08% of the area of the insulation layer, the thermal resistance of the insulation layers is reduced from 10.17 h · ft^2 · °F/Btu (1.79 m^{2}K/W) to 6.26 h · ft^2 · °F/Btu (1.10 m^{2}K/W), a 38% reduction.

To calculate the U-value of the panel, add the individual thermal resistances and take the reciprocal of the total resistances as illustrated in Table 3.5.

Case III—Steel ties plus solid concrete block

To illustrate the effect a 6 in. (150 mm) solid block of concrete around the perimeter of the panel (Fig. 3.5) would have on the U-value, use the parallel-resistance formula for three materials to calculate the thermal resistance.

$$R_t = \frac{R_s R_c R_i}{A_s R_i R_c + A_i R_s R_c + A_c R_s R_i} \tag{3-3}$$

Table 3.6—Thermal properties of sandwich panel with No. 3 (No. 10) bars used as shear ties*

Panel components	Thermal resistance,† (°F · h · ft²/Btu)
Inside air film	0.68
Inner wythe	0.08
Insulation + 2 in. (50 mm) of concrete	2.31
Outer wythe	0.08
Outside air film	0.17
Total thermal resistance	3.32
U-value = 1/3.32 = 0.30 Btu/h · h · ft² · °F	

*And a 6 in. solid block of concrete around the perimeter.
†Multiply °F · h · ft²/Btu values by 0.176 to convert to m²K/W.
Reprinted from "Thermal Properties of Sandwich Panels," W. Calvin McCall, Concrete International, *V. 5, No. 1, Jan. 1985.*

where

R_s = resistance of steel, 0.013 h · ft² · °F/Btu (0.0023 m²K/W);
A_s = percentage of area occupied by steel, 0.08%;
R_i = resistance of insulation + 2 in. (50 mm) of concrete, 10.17 h · ft² · °F/Btu (1.79 m²K/W);
A_i = percentage of area occupied by insulation, 78.92%;
R_c = resistance of concrete, 0.34 h · ft² · °F/Btu (0.059 m²K/W);
A_c = percentage of area occupied by concrete block, 21.25%; and
R_t = thermal resistance of insulating layer.

The total *R*-value for the insulating layer is 2.31 h · ft² · °F/Btu (0.407 m²K/W), which is a reduction of 77% from the 10.17 h · ft² · °F/Btu (1.79 m²K/W) *R*-value of the unpenetrated insulation.

To calculate the *U*-value for this panel, add the individual thermal resistances and take the reciprocal as illustrated in Table 3.6.

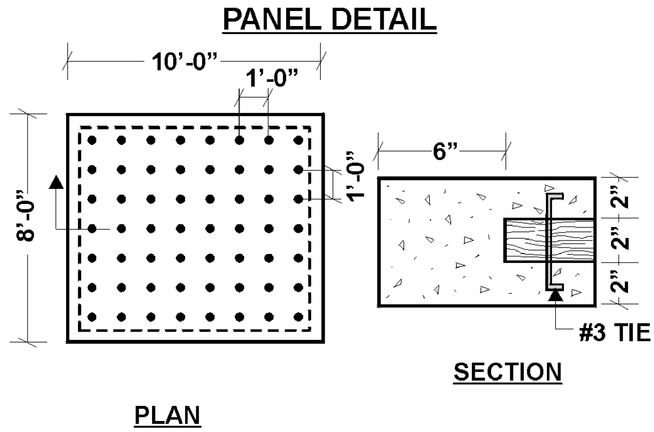


Fig. 3.5—Case III, steel ties plus solid concrete block.

CHAPTER 4—THERMAL MASS AND HOW IT AFFECTS BUILDING PERFORMANCE

4.0—Introduction

The terms thermal mass or thermal inertia describe the absorption and storage of significant amounts of heat in a building or in walls of a building. Concrete and masonry heat and cool slowly and stay warm (or cool) longer than many other building materials. This thermal mass effect delays and reduces heat transfer through a concrete or masonry wall, resulting in a reduction in total heat loss or gain through the building envelope. The reduced heat transfer through concrete or masonry is not a heat loss but rather indicates that some of the heat is stored in the element and later released back into the room. Outdoor daily temperature cycles have a lesser effect on the temperature inside a thermally massive building because massive materials reduce heat transfer and moderate the indoor temperature.

Concrete and masonry walls often perform better than indicated by *R*-values because *R*-values are determined under steady-state temperature conditions. Thus, a thermally massive building will generally use less energy than a frame building insulated by materials of the same *R*-value. Laboratory tests or computer simulations can be used to quantify the energy savings. These methods have permitted building codes to allow lower *R*-values for mass walls than for frame walls to achieve the same thermal performance.

4.1—Factors affecting the thermal mass effect

Many inter-related factors contribute to the actual energy savings from the thermal mass of a building. These include the amount and placement of concrete or masonry materials, insulation, and windows; the building orientation; and the climate. The relative importance of each of these factors depends on the building use and design.

4.1.1 *Thermal diffusivity*—Thermal diffusivity ∝ indicates how quickly a material changes temperature. It is calculated by

$$\propto = k/dc_p = \text{thermal diffusivity (in} \cdot \text{ft}^3\text{/h} \cdot \text{°F) [JW/m}^4\text{]} \quad (3\text{-}4)$$

where

k = thermal conductivity (Btu · in./(h · ft² · °F) [W/(m²K)];
d = density (lb/ft³) [kg/m³]; and
c_p = specific heat (Btu/lb · ft²) [J/kg · K].

A high thermal diffusivity indicates that heat transfer through a material will be fast and the amount of storage will be small. Materials with a high thermal diffusivity respond quickly to changes in temperature. Low thermal diffusivity means a slower rate of heat transfer and a larger amount of heat storage. Materials with low thermal diffusivity respond slowly to an imposed temperature difference. Materials with low thermal diffusivities, such as concrete and masonry, are effective thermal mass elements in a building.

4.1.2 *Heat capacity*—Heat capacity is another indicator of thermal mass, one that is often used in energy codes. Concrete and masonry, because they absorb heat slowly, will generally have higher heat capacities than other materials. Heat capacity is defined as the amount of heat necessary to raise the temperature of a given mass one degree. More simply, it is the product of a mass and its specific heat. In concrete or concrete masonry, the heat capacity of walls is determined by multiplying the wall mass per area (lb/ft²) [kg/m²] by the specific heat (Btu/(lb x °F) [J/(kg · K)]) of the wall material. For example, a single-wythe masonry wall weighing 34 lb/ft² (166 kg/m²) with a specific heat of 0.21 Btu/(lb x °F) [880 J/kg · K]) has a heat capacity of 7.14 Btu/(ft² x °F) [46,080 J/(m²K)]. The total wall heat capacity is simply the sum of the heat capacities of each wall component. Table 4.1 lists specific heat capacity values for concrete masonry materials and, where applicable, for several masonry wall finishes. Tables 4.2 and 4.3 list heat capacity values for several masonry wall

Table 4.1—Specific heat and/or heat capacity of concrete, masonry, and related materials (Btu/ft^2 x °F)*

Material	Density, lb/ft^3	Specific heat, (Btu/lb · °F)*	Heat capacity, (Btu/ft^2 · °F)*	Material		Density, lb/ft^3	Specific heat, (Btu/lb · °F)*	Heat capacity, (Btu/ft^2 · °F)*
Mortar	120	0.20	N/A	Clay brick	Solid 3-5/8 in.*	135	0.20	8.16
Grout	130	0.20	N/A	Gypsum board	3/8 in.*	50	0.26	0.41
Concrete	80	0.21	N/A		1/2 in.*	50	0.26	0.54
	90	0.21	N/A		5/8 in.*	50	0.26	0.68
	100	0.21	N/A	Plaster and stucco	3/8 in.*	120	0.20	1.0
	110	0.21	N/A		1/2 in.*	120	0.20	1.5
	120	0.21	N/A		5/8 in.*	120	0.20	2.0
	130	0.22	N/A					
	140	0.22	N/A					

*Multiply Btu/h · ft^2 · °F values by 5.68 to convert to W/m^{2}K; multiply lb/ft^3 values by 16 to convert to kg/m^3; multiply in. values by 25.4 to convert to mm.
From NCMA TEK 6-16, National Concrete Masonry Association, 1989.

Table 4.2—Heat capacity of ungrouted hollow single wythe walls (Btu/ft^2 x °F)*

Size of CMU and % solid		Density of concrete in CMU, lb/ft^3*						
		80	90	100	110	120	130	140
4 in.*	65	3.40	3.78	4.17	4.55	4.93	5.56	5.96
	78	4.01	4.47	4.94	5.40	5.86	6.60	7.08
	100	5.05	5.64	6.23	6.82	7.41	8.37	8.99
6 in.*	55	4.36	4.87	5.37	5.87	6.38	7.19	7.72
	78	6.04	6.76	7.47	8.18	6.90	10.05	10.80
8 in*	52	5.57	6.23	6.88	7.52	8.17	9.21	9.89
	78	8.17	9.14	10.11	11.08	12.04	13.61	14.63
10 in.*	48	6.50	7.25	8.01	8.76	9.51	10.60	11.38
	78	10.26	11.48	12.71	13.93	15.15	17.13	18.41
12 in.*	48	7.75	8.66	9.57	10.48	11.39	12.86	13.81
	78	12.30	13.77	15.25	16.37	18.20	20.59	22.14

*Multiply Btu/h · ft^2 · °F values by 5.68 to convert to W/m^{2}K; multiply lb/ft^3 values by 16 to convert to kg/m^3; multiply in. values by 25.4 to convert to mm.
Note: Face shell bedding (density of mortar = 120 lb/ft^3; specific heat of mortar = 0.20 [Btu/lb · °F])
From NCMA TEK 6-16, National Concrete Masonry Association, 1989.

systems. When using inch-pound units, a good rule of thumb for calculating heat capacity for concrete masonry walls is to multiply the wall weight per square foot by 0.2, as 0.2 is a good specific heat approximation for concrete masonry materials.

4.1.3 *Insulation*—The physical location of wall insulation relative to wall mass also significantly affects thermal performance. In concrete masonry walls, insulation can be placed on the interior of the wall, integral with the masonry, or on the exterior and is most effective when placed on the exterior. For maximum benefit from thermal mass, the mass should be in direct contact with the interior conditioned air. Because insulation on the interior of the mass thermally isolates the mass from the conditioned space, exterior insulation strategies are usually recommended. For example, rigid board insulation applied on the wall exterior, with a finish applied over the insulation, is generally more energy efficient than furring out the interior of a mass wall and installing batt insulation. Integral insulation strategies include insulating the cores of a masonry unit, using an insulated concrete sandwich panel, or insulating the cavity of a double-wythe masonry wall. In these cases, mass is on both sides of the insulation. Integral insulation allows greater thermal mass benefits than interior insulation but not as much as exterior insulation.

Table 4.3—Heat capacity of grouted single wythe walls (Btu/ft^2 x °F)*

Size of CMU and % solid and grout spacing		Density of concrete in CMU, lb/ft^3*						
		80	90	100	110	120	130	140
6 in.*, 55%	8 in.*	9.46	9.97	10.47	10.97	11.48	12.29	12.82
	16 in.*	6.91	7.42	7.92	8.42	8.93	9.74	10.27
	24 in.*	6.06	6.57	7.07	7.57	8.08	8.89	9.42
	32 in.*	5.64	6.15	6.65	7.15	7.66	8.47	9.00
	40 in.*	5.38	5.89	6.39	6.89	7.40	8.21	8.74
	48 in.*	5.21	5.72	6.22	6.72	7.23	8.04	8.57
8 in.*, 52%	8 in.*	12.97	13.61	14.26	14.90	15.55	16.59	17.27
	16 in.*	9.28	9.92	10.57	11.21	11.86	12.90	13.58
	24 in.*	8.05	8.69	9.34	9.98	10.63	11.67	12.35
	32 in.*	7.44	8.08	8.73	9.37	10.02	11.06	11.74
	40 in.*	7.07	7.71	8.36	9.00	9.65	10.69	11.37
	48 in.*	6.82	7.46	8.11	8.75	9.40	10.44	11.12
10 in.*, 48%	8 in.*	16.59	17.34	18.10	18.85	19.60	20.69	21.47
	16 in.*	11.55	12.30	13.06	13.81	14.56	15.65	16.43
	24 in.*	9.86	10.61	11.37	12.12	12.87	13.96	14.74
	32 in.*	9.02	9.77	10.53	11.28	12.03	13.12	13.90
	40 in.*	8.52	9.27	10.03	10.78	11.53	12.62	13.40
	48 in.*	8.19	8.94	9.70	10.45	11.20	12.29	13.07
12 in.*, 48%	8 in.*	19.94	20.85	21.76	22.67	23.58	25.05	27.00
	16 in.*	13.85	14.76	15.67	16.58	17.49	18.96	19.91
	24 in.*	11.81	12.72	13.63	14.54	15.45	16.92	17.87
	32 in.*	10.80	11.71	12.62	13.53	14.44	15.91	16.86
	40 in.*	10.19	11.10	12.01	12.92	13.83	15.30	16.25
	48 in.*	9.79	10.70	11.61	12.52	13.43	14.90	15.85

*Multiply Btu/h · ft^2 · °F values by 5.68 to convert to W/m^{2}K; multiply lb/ft^3 values by 16 to convert to kg/m^3; multiply in. values by 25.4 to convert to mm.
Note: Face shell bedding (density of mortar = 120 lb/ft^3; specific heat of mortar = 0.20 [Btu/lb · °F])
From NCMA TEK 6-16, National Concrete Masonry Association, 1989.

4.1.4 *Daily temperature changes*—A structure can be designed for energy savings by using the thermal mass effect to introduce thermal lag, which delays and reduces peak temperatures. Figure 4.1(a) illustrates the thermal lag for an

8 in. (20 mm) concrete wall. When outdoor temperatures are at their peak, the indoor air remains relatively unaffected because the outdoor heat has not had time to penetrate the mass. By nightfall, when outside temperatures are falling, the mass begins to release the heat stored during the day, moderating its effect on the interior conditioned space. Temperature amplitudes are reduced and never reach the extremes of the outdoor temperatures. Figure 4.1(a) represents an ideal climate condition for thermal mass in which large outdoor daily temperature swings do not create uncomfortable indoor temperatures due to the mass wall's ability to moderate heat flow into the building. Thermal mass benefits are greater in seasons having large daily temperature swings, as can occur during the spring and fall. In cold climates, the thermal mass effect can be used to collect and store solar energy and internal heat gains generated by office and mechanical equipment. These thermal gains are later reradiated into the conditioned space, thus reducing the heating load. During the cooling season, these same solar and internal gains can be dissipated using night-ventilation strategies (circulating cooler outdoor air over the thermal mass materials or walls). The night venting cools the thermal mass, allowing the interior of the building to remain cool well into the day, reducing the cooling loads and potentially to shifting peak loads.

4.1.5 *Building design*—Building design and use can impact thermal mass because different buildings use energy in different ways. In low-rise residential construction, heating and cooling are influenced by the thermal performance of the building envelope. These buildings are said to have skin-dominated thermal loads, and the effects of thermal mass for low-rise residential buildings are influenced primarily by climate and wall construction.

On the other hand, the thermal mass of commercial and high-rise residential buildings is significantly affected by internal heat gains in addition to the climate and wall construction. Large internal heat gains from lighting, equipment, occupants, and solar transmission through windows create a greater need for thermal mass to absorb heat and delay heat flow. Also, commercial buildings generally have peak cooling loads in the afternoon and have low or no occupancy in the evening. Therefore, delaying the peak load from the afternoon to the evening saves substantial energy because the peak then occurs when the building is unoccupied and sensors can be shifted to a nighttime setting. The benefits of thermal mass in commercial buildings are generally greater than for low-rise residential buildings.

4.2—Determining thermal mass effects

Physical testing and computer simulations may be used to estimate the dynamic thermal performance of concrete and masonry walls and buildings. The calibrated hot box (ASTM C 976) can be used to determine the dynamic thermal performance of concrete and masonry wall sections. These tests, however, are usually limited to 8 ft^2 (0.74 m^2) sections of the opaque wall. A computer is needed to simulate the complex interactions of all building envelope components under constantly varying climatic conditions.

4.2.1 *Calibrated hot-box facilities*—Calibrated hot-box test facilities are used to determine the static and dynamic response of wall specimens to indoor and outdoor temperatures. The hot box consists of two highly insulated chambers clamped tightly together to surround the test wall. Air in each chamber is conditioned by heating and cooling equipment to obtain desired temperatures on each side of the test wall.

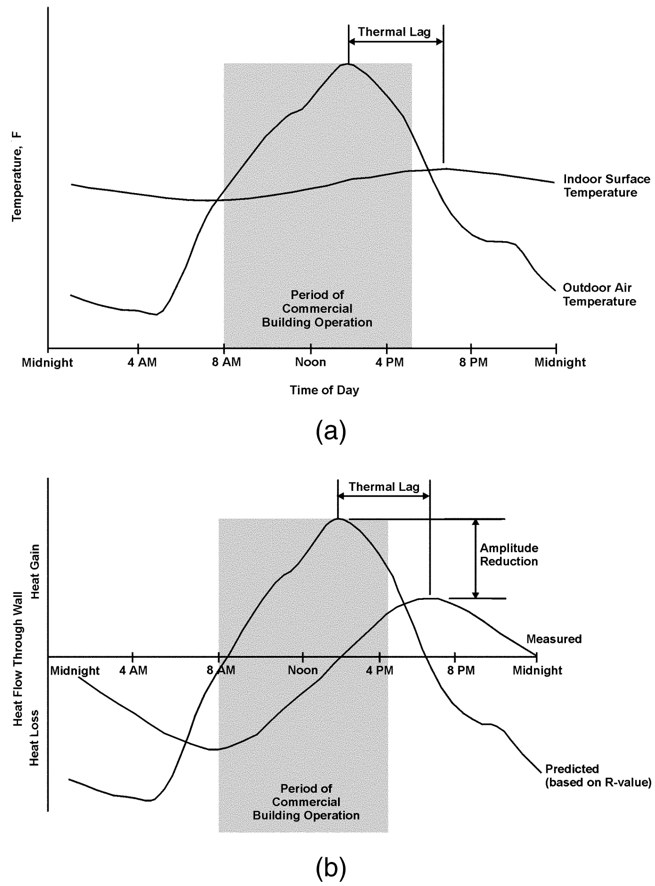


Fig. 4.1—(a) Thermal lag for 8 in. concrete wall; and (b) thermal lag and amplitude reduction for 8 in. concrete wall.

The outdoor (climatic) chamber is cycled between various temperatures. These temperature cycles can be programmed to simulate outdoor daily temperature swings. The indoor (metering) chamber is typically maintained at a constant temperature between 65 and 80 °F (18 and 27 °C) to simulate indoor room conditions.

The chambers and test specimens are instrumented to monitor air and surface temperatures on both sides of the test wall and heating energy input to the indoor chamber. Instruments monitor the energy required to maintain a constant indoor temperature while the outdoor temperature is varied. This energy, when corrected for small thermal losses through the frame, provides a measure of transient heat flow through the test wall.

The calibrated hot box is used to quantify the time lag between outdoor and indoor peak temperatures and the reduction in peak temperatures from outside to inside. The time lag shows the response time of a mass wall to outdoor temperature fluctuations. A long time lag and amplitude reduction relieve excessive cycling of the heating, ventilating, and air conditioning (HVAC) equipment and increase system efficiency. Additional cost savings can result where utility companies offer reduced off-peak energy rates. With a reduction in peak temperatures, less cooling capacity is needed, and the cooling capacity of the HVAC system can frequently be reduced. Similar savings occur for heating. Thermal lag depends on the *R*-value as

Table 4.4—Thermal lag and amplitude reduction measurements from calibrated hot box tests

Wall no.	Thermal lag, h	Amplitude reduction, %
1. 8 x 8 x 16 (200 x 200 x 400 mm) masonry	3.0	18
2. 8 x 8 x 16 (200 x 200 x 400 mm) masonry, with insulated cores.	3.5	28
3. 4-2-4 masonry cavity wall	4.5	40
4. 4-2-4 insulated masonry cavity wall	6.0	38
5. Finished 8 x 8 x 16 (200 x 200 x 400 mm) masonry wall	3.0	51
6. Finished 8 x 8 x 16 (200 x 200 x 400 mm) masonry wall with interior insulation	4.5	31
7. Finished 6 x 8 x 16 (150 x 200 x 400 mm) masonry wall with interior insulation	3.5	10
8. Finished 8 x 4 x 16 (200 x 100 x 400 mm) masonry wall with interior insulation	4.5	27
9. Structural concrete wall	4.0	45
10. Structural lightweight concrete wall	5.5	53
11. Low-density concrete wall	8.5	61
12. Finished, insulated 2 x 4 (38 x 89 mm) wood frame wall	2.5	–6
13. Finished, insulated 2 x 4 (38 x 89 mm) wood frame wall	1.5	7.5
14. Finished, insulated 2 x 4 (38 x 89 mm) wood frame wall	1.5	–4
15. Insulated 2 x 4 (38 x 89 mm) wood frame wall with a masonry veneer	4.0	–6

well as the heat capacity because both of these factors influence the rate of heat flow through a wall.

Two methods of measuring thermal lag use the calibrated hot box. In one method, denoted t_o versus t_i, lag is calculated as the time required for the maximum (or minimum) indoor surface temperature t_i to be reached after the maximum (or minimum) outdoor air temperature t_o is attained (Fig. 4.1(a)). In the second method, denoted q_{ss} versus q_w, lag is calculated as the time required for the maximum (or minimum) heat flow rate q_w to be reached after the maximum (or minimum) heat flow rate based on steady-state predictions q_{ss} is attained (Fig. 4.1(b)). The reduction in amplitude due to thermal mass is defined as the percent reduction in peak heat flow from calibrated hot-box tests when compared with peak heat flow predicted by steady-state analysis. Reduction in amplitude, like thermal lag, is dependent on both the heat-storage capacity and the thermal resistance of the wall. Amplitude reduction for concrete and masonry walls varies between 20 and 60% (Fiorato 1981; Fiorato and Brovinski 1981; Fiorato and Cruz 1981; Peavy et al. 1973; Van Geem 1984; Van Geem 1986a,b; Van Geem et al. 1983a, b,c; Van Geem and Larson 1984).

Table 4.4 shows values of thermal lag and amplitude reduction for various walls when cycled through a specific outside temperature cycle. Other temperature cycles may give different results.

4.2.2 *Computer simulations of buildings*—Computer programs have been developed to simulate the thermal performance of buildings and to predict heating and cooling loads. These programs account for material properties of the building components and the buildings' geometry, orientation, solar gains, internal gains, and temperature-control strategy. Calculations can be performed on an hourly basis using a full year of weather data for a given location. Three such programs currently in use are DOE2, BLAST, and CALPAS3, which are public domain software available through the U.S. Department of Energy (DOE). These computer simulation programs have been well documented and validated through comparisons with monitored results from test cells and full-scale buildings. Although results of such computer analyses will probably not agree completely with actual building performance, relative values between computer-modeled buildings and the corresponding actual buildings are in good agreement.

Table 4.5—1989 CABO model energy code thermal mass benefits for low-rise residential buildings

Required *R*-values for mass walls with exterior insulation					
	R-value required for lightweight walls, (h · ft² · °F/Btu)*				
	5.0	10.0	15.0	20.0	25.0
Heating degree, days (base 65 °F [18 °C])	*R*-value required for corresponding mass walls, (h · ft² · °F/Btu)*				
2000 or less	3.6	6.3	8.6	10.5	12.5
2001 to 4000	3.7	6.7	9.1	11.1	12.5
4001 to 5500	4.0	7.1	10.3	12.5	14.3
5501 to 6500	4.3	8.3	11.5	14.3	16.7
6501 to 8000	4.5	9.1	13.0	16.7	20.0
8001 or more	5.0	10.0	15.0	20.0	25.0
Required *R*-values for mass walls with integral insulation					
	R-value required for lightweight walls, (h · ft² · °F/Btu)*				
	5.0	10.0	15.0	20.0	25.0
Heating degree, days (base 65 °F [18 °C])	*R*-value required for corresponding mass walls, (h · ft² · °F/Btu)*				
2000 or less	3.6	6.7	10.0	12.5	14.3
2001 to 4000	3.7	7.1	10.3	13.3	16.7
4001 to 5500	3.8	7.7	11.1	14.3	16.7
5501 to 6500	4.2	8.3	11.5	15.4	20.0
6501 to 8000	4.5	9.1	13.0	16.7	20.0
8001 or more	5.0	10.0	15.0	20.0	25.0
Required *R*-values for mass walls with interior insulation					
	R-value required for lightweight walls, (h · ft² · °F/Btu)*				
	5.0	10.0	15.0	20.0	25.0
Heating degree, days (base 65 °F [18 °C])	*R*-value required for corresponding mass walls, (h · ft² · °F/Btu)*				
2000 or less	4.0	8.3	13.0	18.2	25.0
2001 to 4000	4.2	8.3	13.0	18.2	25.0
4001 to 5500	4.3	9.1	13.0	18.2	25.0
5501 to 6500	4.5	9.1	14.2	20.0	25.0
6501 to 8000	4.8	10.0	15.0	20.0	25.0
8001 or more	5.0	10.0	15.0	20.0	25.0

*Multiply °F · h · ft²/Btu values by 0.176 to convert to m²K/W.
Note: The 1989 CABO code defines "mass walls" as any wall with a heat capacity greater than or equal to 6 Btu/(ft² · °F).

4.3—Equivalent *R*-values for concrete and masonry walls

Studies of entire buildings by various labs under contract to the DOE show that concrete and masonry buildings of large thermal mass have lower annual heating and cooling loads than other similarly insulated buildings. Therefore, concrete or masonry buildings require less insulation for equivalent performance than buildings with less thermal mass, such as wood or steel stud framing.

Proposed building designs are generally considered to be in compliance with energy codes and standards as long as the

Table 4.6—Determination of equivalent *R*-values using ENVSTD

Envelope system performance compliance calculation program, Version 2.1, ASHRAE/IES Standard 90.1-1989
Energy efficient design of new buildings except low-rise residential buildings

City: 149 New York (Central Park), N.Y. Code <B,C,H>: Both heated and cooled	Building: Two-story commercial Date: Prescriptive req.

	Wall orientation								Weighted	
	N	NE	E	SE	S	SW	W	NW	Average	Criteria
WL area	4000		1200		4000		1200		0.40	0.294
GL area	1600		480		1600		480		WWR	WWR
SCx	0.5		0.5		0.5		0.5		0.50	0.584
PF	0		0		0		0		0.00	0.0
VLT	0		0		0		0		0.00	N/A
Uof	0.33		0.33		0.33		0.33		0.33	0.648
Wall Uo	0.097		0.097		0.097		0.097		0.10	0.099
HC	1		1		1		1		1.00	1
Ins Pos	2		2		2		2		2	N/A
Equip	0.86		0.86		0.86		0.86		0.86	0.860
Lights	1.72		1.72		1.72		1.72		1.72	1.720
DLCF	0		0		0		0		0.00	0.0
	Loads								Total	
Heating	4.646		1.145		3.098		1.179		10.068<	15.038
Cooling	12.540		4.735		16.963		4.950		39.188>	34.880
Total	17.186		5.880		20.061		6.130		49.256<	49.918

City: 149 New York (Central Park), N.Y. Code <B,C,H>: Both heated and cooled	Building: Two-story commercial Date: w/thermal mass

	Wall orientation								Weighted	
	N	NE	E	SE	S	SW	W	NW	Average	Criteria
WL area	4000		1200		4000		1200		0.40	0.294
GL area	1600		480		1600		480		WWR	WWR
SCx	0.5		0.5		0.5		0.5		0.50	0.584
PF	0		0		0		0		0.00	0.0
VLT	0		0		0		0		0.00	N/A
Uof	0.33		0.33		0.33		0.33		0.33	0.648
Wall Uo	0.161		0.161		0.161		0.161		0.16	0.099
HC	8		8		8		8		8.00	1
Ins Pos	2		2		2		2		2	N/A
Equip	0.86		0.86		0.86		0.86		0.86	0.860
Lights	1.72		1.72		1.72		1.72		1.72	1.720
DLCF	0		0		0		0		0.00	0.0
	Loads								Total	
Heating	5.589		1.386		3.709		1.415		12.099<	15.038
Cooling	11.964		4.507		15.996		4.684		37.152>	34.880
Total	17.553		5.893		19.705		6.099		49.251<	49.918

proposed building design will not use more energy than the same building designed according to the prescriptive requirements of the code. For this compliance procedure, the building is analyzed using the prescribed *U*-values listed in the code to determine the estimated annual energy load. Then building parameters such as thermal mass and daylighting, which are not included in some codes when determining the prescriptive requirements, are incorporated. The resulting energy load including these factors is then determined. If this new load is less than the load due to the prescriptive requirements, the building component *U*-values can be increased until the loads are equivalent. Computer programs can do this, but their use may be cumbersome for the majority of building developers, owners, architects, and engineers.

The Council of American Building Officials (CABO) Model Energy Code has adopted simplified tabular *R*-value reductions for mass walls in low-rise residential buildings. These reductions, shown in Table 4.5, were developed by Oak Ridge National Laboratories.

To use Table 4.5, first choose the appropriate part of the table based on the insulation position in the mass wall. Then, read across the top row of the table to the column corresponding to the required *R*-value for a low weight per square foot wall. The reduced *R*-value for a mass wall is then read from this column, at the appropriate climate for the building location. For example, if the code requires an *R*-value of 15 h · ft^2 · °F/Btu (2.64 m^2K/W) walls, a concrete or masonry house with exterior insulation in a 5500 heating degree days (a unit, based on temperature difference and time, used in estimating heating or cooling energy consumption) location would only be required to meet an R-value of 10.3 h · ft^2 · °F/Btu (1.81 m^{2}K/W). The R-value reductions in the Model Energy Code are conservative because they vary only with heating degree days and insulation position. Larger reductions are available by using entire-building simulations.

Reduced R-values based on thermal mass benefits have also been published for commercial and high-rise residential buildings. ASHRAE/IES Standard 90.1-1989 (American Society of Heating, Refrigeration and Air Conditioning Engineers 1989) and the DOE, "Energy Conservation Voluntary Performance Standards for New Commercial and Multi-Family High-Rise Residential Buildings: Mandatory for New Federal Buildings" (U.S. DOE Federal Standard [10 CFR Part 435 Subpart A, 1989]) permit compliance by prescriptive tables or by using the computer program ENVSTD (ENVelope STandarD). ENVSTD permits greater versatility in building design and is much simpler to use than the whole-building computer programs. To determine the required R-values for mass walls, these standards consider many factors, such as lighting and equipment loads, projection factors for shading, shading coefficients for glazing, and use of daylighting techniques, in addition to climate, heat capacity, and insulation position.

As an example, assume that the building code requires an overall wall U-value of 0.19 Btu/h · ft^2 · °F (1.08 W/m^{2}K) (or an R-value of 5.1 h · ft^2 · °F/Btu [0.9 m^{2}K/W]) for a low-rise commercial building in New York City. If the proposed design incorporates 40% triple glazing, $U_{glazing}$ = 0.33 Btu/h · ft^2 · °F (1.83 W/m^{2}K), then an opaque wall with a U-value of 0.097 Btu/h · ft^2 · °F (0.55 W/m^{2}K) will meet the standard. Table 4.6 shows that the total annual load for this building is 49.256, according to ENVSTD. If the building design uses an integrally insulated concrete or masonry wall system with a heat capacity of 8 Btu/h · °F (4.22 W/K), the U-value of the wall can be increased to 0.161 Btu/h · ft^2 · °F (0.914 W/m^{2}K), and the total annual load is slightly lower than the load for the prescriptive building. In this example, by using ENVSTD, the R-value of the opaque wall can be reduced from 10.3 to 6.2 h · ft^2 · °F/Btu (1.81 to 1.09 m^2 K/W) due to thermal mass and still maintain the same energy performance.

4.4—Interior thermal mass

Up to this point, most of the information presented in this chapter has focused on the effects of thermal mass in the exterior envelopes of buildings. Concrete and masonry can also help improve building occupant comfort and save additional energy when used in building interiors. When designing interior mass components, R-values are not important because there is no significant heat transfer through an interior wall or floor. Instead, heat is absorbed from the room into the mass then re-released back into the room. In other words, the interior mass acts as a storage facility for energy. A concrete floor in a sunroom absorbs solar energy during the day, then releases the stored warmth during the cooler nighttime hours.

Interior thermal mass acts to balance temperature fluctuations within a building that occur from day to night or from clouds intermittently blocking sunlight. Because of this flywheel effect, the temperature inside a building changes slowly. This keeps the building from cooling too fast at night during the heating season or heating too quickly during the day in the cooling season.

To use interior thermal mass effectively, carefully choose the heat capacity and properly locate the concrete and masonry components. Concrete or masonry as thin as 3 in. (75 mm) is sufficient to moderate the interior temperature because surface area is more important than thickness for interior thermal mass. A large surface area in contact with conditioned air tends to stabilize interior temperatures. Concrete or masonry distributed in a thin layer over the walls and floors of interior rooms is more effective than the same amount of mass placed in one thick, solid thermal mass wall. Other designs may require different placements of thermal mass (Balik and Barney 1981a,b,c; Balik and Barney 1983; Catani and Goodwin 1976, 1977; Goodwin and Catani 1979a,b; Mitalas 1979; Portland Cement Association 1981, 1982; Ruday and Dougall 1979). For passive solar applications, the mass should be in direct contact with the sunlight for maximum effectiveness (Total Environment Action, Inc. 1980).

CHAPTER 5—THERMAL PROPERTIES FOR PASSIVE SOLAR DESIGN

5.0—Introduction

Passive solar buildings use three basic components: glazing, thermal mass, and ventilation. South-facing glass is used as the heat collector. Glass in other parts of the building is minimized to reduce heat loss or unwanted heat gain. Thermal mass is used to store heat gained through the glass and to maintain interior comfort. The building ventilation system distributes air warmed by solar gains throughout the building (Brick Industry Association 1980; Illinois-Indiana Masonry Council 1981; Mazria 1979; Total Environment Action, Inc. 1980).

Passive solar buildings require a large thermal mass to adequately store solar gains and maintain comfort in both heating and cooling seasons. The heat-storage capacity of concrete and masonry materials is determined by a variety of thermal properties, such as absorbtivity, conductivity, specific heat, diffusivity, and emissivity. This chapter describes these properties, discusses their impact on passive solar buildings, and provides design values. These data allow designers to more accurately predict the performance of thermal storage mass and to choose appropriate materials for a particular design.

5.1—Thermal properties

Thermal properties of the storage mass must be known to size HVAC equipment, maintain comfort in the building, and determine the optimal amount and arrangement of the thermal mass. For most passive solar applications, heat energy absorbed during the day is preferably released at night, as opposed to the next day. Therefore, the thermal mass storage effectiveness depends on the heat-storage capacity of the mass and the rate of heat flow through the mass.

5.1.1 *Conductivity*—Conductivity, defined in Chapter 2, indicates how quickly or easily heat flows through a material. In passive solar applications, conductivity allows the solar heat to be transferred beyond the surface of the mass for more effective storage. Materials with very high conductivity values, however, should be avoided because high conductivity can shorten the time lag for heat delivery.

5.1.2 *Absorbtivity*—The amount of heat absorbed by a wall depends on its absorbtivity and the solar radiation incident on the wall. Absorbtivity is a measure of the efficiency of receiving radiated heat and is the fraction of incident solar radiation that is absorbed by a given material, as opposed to being reflected or transmitted. For opaque materials, such as concrete and masonry, solar radiation not absorbed by the wall is reflected away from it. Absorbtivity is a relative value; an absorbtivity of 1.0 indicates that a material absorbs all incident radiated heat and reflects none.

The absorbtivity of nonmetallic materials is a surface effect largely dependent on surface color. Dark surfaces have higher absorbtivities than light surfaces because they absorb more heat, while light surfaces reflect more heat than they absorb.

Sunlit thermal-mass floors should be relatively dark in color to absorb and store heat more efficiently. Robinson (1980) concludes that reds, browns, blues, and blacks will perform adequately for passive solar storage. Nonmass walls and ceilings should be light in color to reflect solar radiation to the thermal storage mass and to help distribute light more evenly.

Rough-textured surfaces, such as split-faced block or stucco, provide more surface area for collection of solar energy than smooth surfaces, but this advantage in solar energy collection has not been thoroughly investigated. Solar absorbtivity is usually determined using ASTM E 434. This test subjects a specimen to simulated solar radiation. Radiant energy absorbed by a specimen and emitted to the surroundings causes the specimen to reach an equilibrium temperature that is dependent on the ratio of absorbtivity to emissivity. Solar absorbtivity is then determined from the known emissivity.

5.1.3 *Emissivity*—Emissivity, sometimes called emittance, describes how efficiently a material transfers energy by radiation heat transfer or how efficiently a material emits energy. Like absorbtivity, emissivity is a unitless value defined as the fraction of energy emitted or released from a material, relative to the radiation of a perfect emitter or blackbody. For thermal storage, high-emissivity materials are used to effectively release stored solar heat into the living areas.

The ability of a material to emit energy increases as the temperature of the material increases. Therefore, emissivity is a function of temperature and increases with increasing temperature. For the purposes of passive solar building design, emissivity values at room temperature are used. Mazria (1979) and other researchers frequently assume an emissivity value of 0.90 for all nonmetallic building materials.

Emissivity is determined using either emitter 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 such as ASTM E 408 measures emitted radiation directed into a sensor.

5.1.4 *Other factors*—Specific heat is a material property that describes the ability of a material to store heat. 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 amount of heat required to raise the temperature of an equal mass of water by one degree. Materials with high specific heat values are effectively used for thermal storage in passive solar designs. Values of specific heat for concrete and masonry materials vary between 0.19 and 0.22 Btu/lb · °F (0.79 and 0.92 kJ/kg · K).

Some heat-capacity storage is present in all buildings in the framing, gypsum board, furnishings, and floors. Home furnishings typically have a heat capacity of approximately 0.18 Btu/(h · °F). A larger amount of thermal mass, however, is required in passive solar buildings. Walls and floors with high heat capacities are desirable for passive solar storage applications. Heat capacity is discussed in Section 4.1.2.

In addition to heat capacity, another property that is often used in passive solar design references is thermal diffusivity. Thermal diffusivity is a measure of heat transport relative to energy storage and is defined in Section 4.1.1. Materials with high thermal diffusivities are more effective at heat transfer than heat storage. Therefore, materials with low thermal diffusivities are desirable for storing solar energy.

5.2—Incorporating mass into passive solar designs

In addition to the material properties discussed here, location of thermal mass materials is also important in passive solar applications. For most materials, the effectiveness of thermal mass in the floor or interior wall increases proportionally with a thickness up to approximately 3 to 4 in. (75 to 100 mm). Beyond that, the effectiveness does not increase as significantly. A 4 in. (100 mm) thick mass floor is about 30% more effective at storing direct sunlight than a 2 in. (50 mm) thick mass floor. A 6 in. (150 mm) thick mass floor, however, will only perform about 8% better than the 4 in. (100 mm) floor. For most applications, 3 to 4 in. (75 to 100 mm) thick mass walls and floors maximize the amount of storage per unit of wall or floor material, unless thicker elements are required for structural or other considerations. Distributing thermal mass evenly around a room stores heat more efficiently and improves comfort by reducing localized hot or cold spots.

Location of thermal mass within a passive solar building is also important in determining a building's efficiency and comfort. Mass located in the space where solar energy is collected is about four times more effective than mass located outside the collection area. If the mass is located away from the sunlit area, it is considered to be convectively coupled. Convectively coupled mass provides a mechanism for storing heat away from the collection area through natural convection and improves comfort by damping indoor temperature swings.

Covering mass walls and floors with materials having *R*-values larger than approximately 0.5 h · ft^2 · °F/Btu (0.09 m^{2}K/W) and low thermal diffusivities will reduce the daily heat-storage capacity. Coverings such as surface bonding, thin plaster coats, stuccos, and wallpapers do not significantly reduce the storage capacity. Materials such as cork, paneling with furring, and sound boards are best avoided. Direct attachment of gypsum board is acceptable if it is firmly adhered to the block or brick wall surface (no air space between gypsum board and masonry). Exterior mass walls should be insulated on the exterior or within the cores of concrete block to maximize the effectiveness of the thermal mass. Thermal mass can easily be incorporated into the floors of many buildings using slab-on-grade or hollow precast floors. If mass is used in floors, it will be much more effective if sunlight falls directly on it. Effective materials for floors include painted, colored, or vinyl-covered concrete; brick or concrete pavers; quarry tile; and dark-colored ceramic tile.

As more south-facing glass is used, more thermal mass should be provided to store heat gains and prevent the building from overheating. Although the concept is simple, in practice the relationship between the amount of glazing and the amount of mass is complicated by many factors. From a comfort standpoint, it would be difficult to add too much mass. Thermal mass will hold solar gains longer in winter and keep buildings cooler in summer. Thermal mass has a cost, however, so adding too much can be uneconomical. Design guidance on passive solar buildings is beyond the scope of this text. Several references exist on the subject (Brick Industry Association 1980; Illinois-Indiana Masonry Council 1981; Mazria 1979; Total Environment Action, Inc. 1980).

5.3—Summary

Passive solar buildings represent a specialized application of thermal mass for solar heat storage, retention, and reradiation. To accomplish these tasks, the storage medium should have certain thermal characteristics. Thermal conductivity should be high enough to allow the heat to penetrate into the storage material but not so high that the storage time or thermal lag is shortened. Solar absorbtivity should be high, especially for mass floors, to maximize the amount of solar energy that can be stored.

Thermal storage materials should have high-emissivity characteristics to efficiently reradiate the stored energy back into the occupied space. Specific heat and heat capacity should be high to maximize the amount of energy that can be stored in a given amount of material.

Concrete and masonry materials fulfill all of these requirements for effective thermal storage. These materials have been used with great success in passive solar buildings to store the collected solar energy, prevent overheating, and reradiate energy to the interior space when needed.

CHAPTER 6—CONDENSATION CONTROL

6.0—Introduction

Moisture condensation on the interior surfaces of a building envelope is unsightly and can cause damage to the building or its contents. Moisture condensation within a building wall or ceiling assembly can be even more undesirable because it may not be noticed until damage has occurred.

All air contains water vapor, and warm air carries more water vapor than cold air. Moisture, in the form of water vapor, is added to the air by respiration, perspiration, bathing, cooking, laundering, humidifiers, and industrial processes. When the air contacts cold surfaces, the air may be cooled below its dew point, permitting condensation to occur. Dew point is the temperature at which water vapor condenses.

Once condensation occurs, the relative humidity of the interior space of a building cannot be increased because any additional water vapor will simply condense on the cold surface. The inside surface temperature of a building assembly effectively limits the relative humidity of air contained in an interior space.

6.1—Prevention of condensation on wall surfaces under steady-state analysis

Condensation on interior surfaces can be prevented by using materials with U-values such that the surface temperature will not fall below the dew point temperature of the air in the room. The amount of thermal resistance that should be provided to avoid condensation can be determined from the following relationship

$$R_t = R_{fi}\frac{(t_i - t_o)}{(t_i - t_s)} \tag{6-1}$$

R_t = thermal resistance of wall assembly h · ft^2 · °F/Btu (m^{2}K/W);
R_{fi} = thermal resistance of interior surface air film h · ft^2 · °F/Btu (m^{2}K/W);
t_i = indoor air temperature °F (°C);
t_o = outdoor air temperature °F (°C); and
t_s = saturation, or dew point temperature °F (°C).

Due to lag time associated with the thermal mass effect, the steady-state analysis of condensation is conservative for masonry walls. Dew point temperatures to the nearest degree Fahrenheit for various values of t_i and relative humidity are shown in Table 6.1.

For example, R_t is to be determined when the room temperature and relative humidity are 70 °F (21 °C) and 40% respectively, and t_o during the heating season is –10 °F (–24 °C). From Table 6.1, the dew point temperature t_s is 45 °F (7 °C) and because the resistance of the interior air film f_i is 0.68 h · ft^2 · °F/Btu (0.12 m^{2}K/W)

$$R_{fi} = 0.68 \text{ h} \cdot \text{ft}^2 \cdot \text{°F/Btu } [0.12 \text{ m}^2\text{K/W}]$$

$$R_t = \frac{0.68[70-(-10)]}{[70-45]} = 2.18 \text{ h} \cdot \text{ft}^2 \cdot \text{°F/Btu } [0.38 \text{ m}^2\text{K/W}]$$

6.2—Prevention of condensation within wall constructions

Water vapor in air is a gas and it diffuses through building materials at rates that depend on vapor permeabilities of materials and vapor-pressure differentials. Colder outside air temperatures increase the water-vapor-pressure differential with the warm inside air; this increases the driving force moving the inside air to the outside.

Leakage of moisture-laden air into an assembly through small cracks can be a greater problem than vapor diffusion. The passage of water vapor through a material is, in itself, generally not harmful. It becomes of consequence when, at some point along the vapor flow path, vapors fall below the dew point temperature and condense.

Water-vapor permeability and permeances of some building materials are shown in Table 6.2. Water-vapor permeability μ (gr/(h · ft^2 · (in. Hg)/in.) (ng/s · m · Pa) is defined as the rate of water-vapor transmission per unit area of a body between two specified parallel surfaces induced by a unit vapor-pressure difference between the two surfaces. When properly used, low-permeability materials keep moisture from entering a wall or roof assembly, whereas high permeability materials allow moisture to escape. Water-vapor permeance M is defined as the water-vapor permeability for a thickness other than the unit thickness to which μ refers. Hence, $M = \mu/l$ where l is the flow path, or material, thickness (gr/(h · ft^2 · [in. Hg]) (ng/s · m^2 · Pa).

When a material such as plaster or gypsum board has a permeance too high for the intended use, one or two coats of paint are often enough to lower the permeance to an acceptable level. Alternatively, a vapor retarder can be used directly behind such products.

Polyethylene sheet, aluminum foil, and roofing materials are commonly used as vapor retarders. Proprietary vapor retarders, usually combinations of foil, polyethylene, and asphalt, are frequently used in freezer and cold-storage construction. Concrete is a relatively good vapor retarder. Permeance is a function of the *w/c* of the concrete. A low *w/c* results in concrete with low permeance.

Where climatic conditions demand insulation, a vapor retarder is generally needed to prevent condensation. Closed-cell insulation, if properly applied, will serve as its

Table 6.1—Dew-point temperatures t_s,* °F (°C)

Dry bulb or room temperature	Relative humidity, %									
	10	20	30	40	50	60	70	80	90	100
40 (4)	–7	6	14	19	24	28	31	34	37	40
45 (7)	–3	9	18	23	28	32	36	39	42	45
50 (10)	–1	13	21	27	32	37	41	44	47	50
55 (13)	5	17	26	32	37	41	45	49	52	55
60 (16)	7	21	30	36	42	46	50	54	57	60
65 (18)	11	24	33	40	46	51	55	59	62	65
70 (21)	14	27	38	45	51	56	60	63	67	70
75 (24)	17	32	42	49	55	60	64	69	72	75
80 (27)	21	36	46	54	60	65	69	73	77	80
85 (29)	23	40	50	58	64	70	74	78	82	85
90 (32)	27	44	55	63	69	74	79	83	85	90

*Temperatures are based on barometric pressure of 29.92 in. Hg^2 (101.3 KPa).

Table 6.2—Typical permeance (*M*) and permeability (μ) values*

Material	$M^†$ perms	$μ^†$ perm-in.
Concrete (1:2:4 mixture)‡		3.2
Wood (sugar pine)	—	0.4 to 5.4
Expanded polystyrene (extruded)	—	1.2
Paint—two coats		
Asphalt paint on plywood	0.4	—
Enamels on smooth plaster	0.5 to 1.5	—
Various primers plus one coat flat oil paint on plaster	1.6 to 3.0	—
Expanded polystyrene (bead)	—	2.0 to 5.8
Plaster on gypsum lath (with studs)	20.00	—
Gypsum wallboard, 0.375 in. (9.5 mm)	50.00	—
Polyethylene, 2 mil (0.05 mm)	0.16	—
Polyethylene, 10 mil (0.3 mm)	0.03	—
Aluminum foil, 0.35 mil (0.009 mm)	0.05	—
Aluminum foil, 1 mil (0.03 mm)	0.00	—
Built-up roofing (hot mopped)	0.00	—
Duplex sheet, asphalt laminated aluminum foil one side	0.002	—

*ASHRAE Handbook, Chapter 22, Table 7.
†Multiply (perms) values by (5.721 E-11) to convert to Kg/(Pa · s · m^2); multiply perm in. values by (1.453 E-12) to convert to Kg/(Pa · s · m).
‡Permeability for concrete varies depending on the concrete's water-cement ratio (*w/c*) and other factors.

own vapor retarder but should be taped at all joints to be effective. For other insulation materials, a vapor retarder should be applied to the warm side of the insulation for the season representing the most serious condensation potential—that is, on the interior in cold climates and on the exterior in hot and humid climates. Low-permeance materials on both sides of insulation, creating a double vapor retarder, can trap moisture within an assembly and should be avoided.

CHAPTER 7—REFERENCES

7.1 — Referenced standards and reports

The standards and reports listed below were the latest editions at the time this document was prepared. Because these documents are revised frequently, the reader is advised to contact the proper sponsoring group if it is desired to refer to the latest version.

American Society for Testing and Materials

C 177 Test Method for Steady-State Thermal Transmission Properties by Means of the Guarded Hot Plate
C 236 Test Method for Steady-State Thermal Performance of Building Assemblies by Means of a Guarded Hot Box
C 976 Test Method for Thermal Performance of Building Assemblies by Means of a Calibrated Hot Box
E 408 Total Normal Emittance of Surfaces Using Inspection-Meter Techniques
E 434 Calorimetric Determination of Hemispherical Emittance Using Solar Simulation
E 917 Practice for Measuring Life-Cycle Costs of Buildings and Building System

These publications may be obtained from this organization:

ASTM
100 Barr Harbor Drive
West Conshohocken, PA 19428

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