CHAPTER 26

HEAT, AIR, AND MOISTURE CONTROL IN BUILDING ASSEMBLIES—MATERIAL PROPERTIES

THERMAL PROPERTIES 26.1
Air Spaces 26.1
Building and Thermal Insulation Materials 26.2
AIR TRANSMISSION AND HYGRIC PROPERTIES 26.13
Air Barriers and Water Vapor Retarders 26.13
Air Transmission and Water Vapor Property Data 26.15
Moisture Storage Data 26.15

THIS chapter presents thermal and water vapor transmission data based on steady-state or equilibrium conditions. This information can be used in the simplified calculation methods described in Chapter 27, or in software-based methods that develop step-wise steady-state conditions into a time-dependent solution. Chapter 4 covers heat transfer under transient or changing temperature conditions. Chapter 25 discusses combined heat-air-moisture transport. For information on insulation for mechanical systems, see Chapter 23.

Ideal conditions of components and installations are assumed in calculating overall R-values (i.e., insulating materials are of uniform nominal thickness and thermal resistance, air spaces are of uniform thickness and surface temperature, moisture effects are not involved, and installation details are in accordance with design). Robinson et al. (1957) showed that measured values differ from calculated values for certain insulated constructions. To account for this, some engineers moderately decrease calculated R-values.

The overall thermal resistance of an assembly comprises its surface-to-surface conductance and the resistances to heat transfer between assembly surfaces and interior and exterior spaces. This chapter includes standardized surface and air cavity resistances in typical building assemblies. Typical thermal properties (density, thermal conductivity, and specific heat) are provided for a wide range of building materials.

Material properties related to hygric performance (e.g., water vapor permeance, permeability, air permeance, sorption isotherms) are also given for several materials.

THERMAL PROPERTIES

AIR SPACES

Surface Resistances

As explained in Chapter 25, the overall R-value of an assembly comprises its surface-to-surface conductance C and the resistances to heat transfer between assembly surfaces and interior and exterior spaces (R_i and R_o, respectively). Table 1 presents standardized surface resistances R as well as conductances h_i and h_o, which are sometimes referenced in fenestration applications [see Chapter 15 and ASHRAE (1998)]. As shown, the resistance to heat transfer from a heated area to the surface (or from the surface to a cooler area) through natural convection (called "still air" in Table 1, although air does move through buoyancy) depends on the position of the surface, direction of heat transfer, temperature of the surface and the air, difference between the surface temperature and that of the surroundings, and the surface's long-wave emittance. Where air is moved by wind or fans, the resistance to heat transfer to or from the surface depends on air speed, surface temperature, difference between the surface temperature and that of the surroundings, and the surface's long-wave emittance. Values in Table 1 are for typical situations encountered in construction. For other temperatures and conditions, use ASHRAE (1998) to determine surface conductances or resistances.

Table 1 Surface Conductances and Resistances for Air

Position of Surface	Direction of Heat Flow	Surface Emittance, ε: Nonreflective ε = 0.90 h_i	R	Reflective ε = 0.20 h_i	R	Reflective ε = 0.05 h_i	R
Still Air							
Horizontal	Upward	1.63	0.61	0.91	1.10	0.76	1.32
Sloping at 45°	Upward	1.60	0.62	0.88	1.14	0.73	1.37
Vertical	Horizontal	1.46	0.68	0.74	1.35	0.59	1.70
Sloping at 45°	Downward	1.32	0.76	0.60	1.67	0.45	2.22
Horizontal	Downward	1.08	0.92	0.37	2.70	0.22	4.55
Moving Air (any position)		h_o	R				
15 mph wind (for winter)	Any	6.00	0.17	—	—	—	—
7.5 mph wind (for summer)	Any	4.00	0.25	—	—	—	—

Notes:
1. Surface conductance h_i and h_o measured in Btu/h·ft^2·°F; resistance R in h·ft^2·°F/Btu.
2. No surface has both an air space resistance value and a surface resistance value.
3. Conductances are for surfaces of the stated emittance facing virtual black-body surroundings at same temperature as ambient air. Values based on surface/air temperature difference of 10°F and surface temperatures of 70°F.
4. See Chapter 4 for more detailed information.
5. Condensate can have significant effect on surface emittance (see Table 2).

Note that it is not appropriate to compute an overall R-value that assigns both a surface resistance and an air-space resistance to the same air space; that should be considered double-counting, and is not an accurate representation of the thermal resistance of the assembly (see Note 2 in Table 1).

Air Cavities

When air is enclosed in the assembly, the enclosed cavity's thermal resistance can contribute to the resistance of the overall assembly. Even under steady-state conditions, convective air movement driven by buoyancy defines the thermal resistance of the cavity. Like the surface condition described above, the magnitude of this resistance depends on the slope of the cavity, direction of heat transfer, mean temperature in the cavity, and temperature and long-wave emittance of cavity surfaces. Table 3 provides thermal resistance values for enclosed cavities for various conditions, depending on the

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The preparation of this chapter is assigned to TC 4.4, Building Materials and Building Envelope Performance.

Table 2 Emittance Values of Various Surfaces and Effective Emittances of Air Spaces[a]

Surface	Average Emittance ε	Effective Emittance ε_{eff} of Air Space	
		One Surface Emittance ε; Other, 0.9	Both Surfaces Emittance ε
Aluminum foil, bright	0.05	0.05	0.03
Aluminum foil, with condensate just visible (>0.7 g/ft^2)	0.30[b]	0.29	—
Aluminum foil, with condensate clearly visible(>2.9 g/ft^2)	0.70[b]	0.65	—
Aluminum sheet	0.12	0.12	0.06
Aluminum coated paper, polished	0.20	0.20	0.11
Steel, galvanized, bright	0.25	0.24	0.15
Aluminum paint	0.50	0.47	0.35
Building materials: wood, paper, masonry, nonmetallic paints	0.90	0.82	0.82
Regular glass	0.84	0.77	0.72

[a] Values apply in 4 to 40 µm range of electromagnetic spectrum.
[b] Values based on data in Bassett and Trethowen (1984).

combined or **effective emittance** of the cavity's hot and cold surfaces. The effective emittance is the combined value of the emittances of both surfaces according to $1/\varepsilon_{eff} = 1/\varepsilon_1 + 1/\varepsilon_2 - 1$. Some values for combined emittance are listed in Table 2, to be used to determine the resistance of cavities in Table 3.

Tables 2 and 3 give values for well-sealed cavities constructed with care. Field applications can differ substantially from laboratory test conditions. Air gaps into the cavity can seriously degrade thermal performance because of air movement through both natural and forced convection. Sabine et al. (1975) found that tabular values are not necessarily additive for multiple-layer, low-emittance air spaces, and tests on actual constructions should be conducted to accurately determine thermal resistance values.

Values for foil insulation products supplied by manufacturers must also be used with caution because they apply only to systems that are identical to the configuration in which the product was tested. In addition, surface oxidation, dust accumulation, condensation, and other factors that change the condition of the low-emittance surface can reduce the thermal effectiveness of these insulation systems (Hooper and Moroz 1952). Deterioration results from contact with several types of solutions, either acidic or basic (e.g., wet cement mortar, preservatives found in decay-resistant lumber). Polluted environments may cause rapid and severe material degradation. However, site inspections show a predominance of well-preserved installations, and only a small number of cases in which rapid and severe deterioration has occurred. An extensive review of the reflective building insulation system performance literature is provided by Goss and Miller (1989).

Note that reflective foils are only effective if the reflective surface faces an air space, because radiative heat transfer cannot be reduced where there is no air space to allow radiative heat transfer. Also, multiple layers of reflective foil are no more effective than a single layer, unless the reflective surfaces adjoin different air spaces in the assembly.

Figure 1 shows how surface conductance for surfaces with different roughness is affected by air movement. Other tests on smooth surfaces show that the average value of the convection part of surface conductance decreases as surface length increases.

The following conditions are assumed in calculating design R-values for construction assemblies:

- Equilibrium or steady-state heat transfer, disregarding effects of thermal storage
- Surrounding surfaces at ambient air temperature
- Exterior wind velocity of 15 mph for winter (surface with R = 0.17 h·ft^2·°F/Btu) and 7.5 mph for summer (surface with R = 0.25 h·ft^2·°F/Btu)
- Surface emittance of ordinary building materials is 0.9

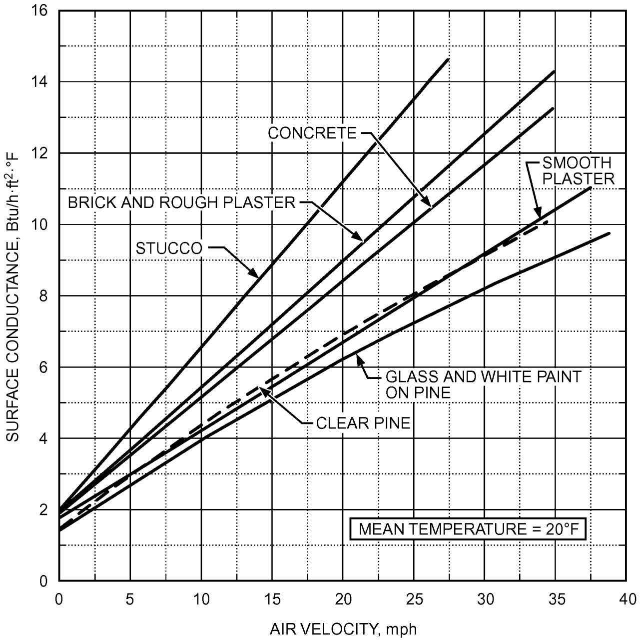

Fig. 1 Surface Conductance for Different Surfaces as Affected by Air Movement

BUILDING AND THERMAL INSULATION MATERIALS

Thermal Insulation Materials

When properly applied, thermal insulation materials retard conductive, convective, and radiative heat flux. Thermal insulation in building envelopes does at least one of the following:

- Conserves energy by reducing the building's heat loss or gain
- Controls surface temperatures for comfort
- Helps control temperatures in a structure
- Reduces the tendency for water condensation on inside and outside surfaces
- Reduces temperature fluctuations in unconditioned or partly conditioned spaces

Thermal insulation materials may also serve additional functions, although these should be consistent with the capabilities of the materials and their primary purpose:

- Adding structural strength to a wall, ceiling, or floor section
- Providing support for a surface finish
- Impeding water vapor transmission and air infiltration
- Preventing or reducing damage to structures from exposure to fire and freezing conditions
- Reducing noise and vibration

Poorly designed or improperly installed thermal insulation may promote interstitial moisture condensation and subsequent damage within a building envelope. When thermal insulation is used to control heat flow at all temperatures, the limiting value is its survival temperature.

Table 3 Thermal Resistances of Plane Air Spaces,[a,b,c] h·ft²·°F/Btu

Position of Air Space	Direction of Heat Flow	Air Space		Effective Emittance ε_{eff}[d,e]									
				0.5 in. Air Space[c]					0.75 in. Air Space[c]				
		Mean Temp.,[d] °F	Temp. Diff.,[d] °F	0.03	0.05	0.2	0.5	0.82	0.03	0.05	0.2	0.5	0.82
Horiz.	Up ↑	90	10	2.13	2.03	1.51	0.99	0.73	2.34	2.22	1.61	1.04	0.75
		50	30	1.62	1.57	1.29	0.96	0.75	1.71	1.66	1.35	0.99	0.77
		50	10	2.13	2.05	1.60	1.11	0.84	2.30	2.21	1.70	1.16	0.87
		0	20	1.73	1.70	1.45	1.12	0.91	1.83	1.79	1.52	1.16	0.93
		0	10	2.10	2.04	1.70	1.27	1.00	2.23	2.16	1.78	1.31	1.02
		−50	20	1.69	1.66	1.49	1.23	1.04	1.77	1.74	1.55	1.27	1.07
		−50	10	2.04	2.00	1.75	1.40	1.16	2.16	2.11	1.84	1.46	1.20
45° Slope	Up ↗	90	10	2.44	2.31	1.65	1.06	0.76	2.96	2.78	1.88	1.15	0.81
		50	30	2.06	1.98	1.56	1.10	0.83	1.99	1.92	1.52	1.08	0.82
		50	10	2.55	2.44	1.83	1.22	0.90	2.90	2.75	2.00	1.29	0.94
		0	20	2.20	2.14	1.76	1.30	1.02	2.13	2.07	1.72	1.28	1.00
		0	10	2.63	2.54	2.03	1.44	1.10	2.72	2.62	2.08	1.47	1.12
		−50	20	2.08	2.04	1.78	1.42	1.17	2.05	2.01	1.76	1.41	1.16
		−50	10	2.62	2.56	2.17	1.66	1.33	2.53	2.47	2.10	1.62	1.30
Vertical	Horiz. →	90	10	2.47	2.34	1.67	1.06	0.77	3.50	3.24	2.08	1.22	0.84
		50	30	2.57	2.46	1.84	1.23	0.90	2.91	2.77	2.01	1.30	0.94
		50	10	2.66	2.54	1.88	1.24	0.91	3.70	3.46	2.35	1.43	1.01
		0	20	2.82	2.72	2.14	1.50	1.13	3.14	3.02	2.32	1.58	1.18
		0	10	2.93	2.82	2.20	1.53	1.15	3.77	3.59	2.64	1.73	1.26
		−50	20	2.90	2.82	2.35	1.76	1.39	2.90	2.83	2.36	1.77	1.39
		−50	10	3.20	3.10	2.54	1.87	1.46	3.72	3.60	2.87	2.04	1.56
45° Slope	Down ↘	90	10	2.48	2.34	1.67	1.06	0.77	3.53	3.27	2.10	1.22	0.84
		50	30	2.64	2.52	1.87	1.24	0.91	3.43	3.23	2.24	1.39	0.99
		50	10	2.67	2.55	1.89	1.25	0.92	3.81	3.57	2.40	1.45	1.02
		0	20	2.91	2.80	2.19	1.52	1.15	3.75	3.57	2.63	1.72	1.26
		0	10	2.94	2.83	2.21	1.53	1.15	4.12	3.91	2.81	1.80	1.30
		−50	20	3.16	3.07	2.52	1.86	1.45	3.78	3.65	2.90	2.05	1.57
		−50	10	3.26	3.16	2.58	1.89	1.47	4.35	4.18	3.22	2.21	1.66
Horiz.	Down ↓	90	10	2.48	2.34	1.67	1.06	0.77	3.55	3.29	2.10	1.22	0.85
		50	30	2.66	2.54	1.88	1.24	0.91	3.77	3.52	2.38	1.44	1.02
		50	10	2.67	2.55	1.89	1.25	0.92	3.84	3.59	2.41	1.45	1.02
		0	20	2.94	2.83	2.20	1.53	1.15	4.18	3.96	2.83	1.81	1.30
		0	10	2.96	2.85	2.22	1.53	1.16	4.25	4.02	2.87	1.82	1.31
		−50	20	3.25	3.15	2.58	1.89	1.47	4.60	4.41	3.36	2.28	1.69
		−50	10	3.28	3.18	2.60	1.90	1.47	4.71	4.51	3.42	2.30	1.71
		Air Space		1.5 in. Air Space[c]					3.5 in. Air Space[c]				
Horiz.	Up ↑	90	10	2.55	2.41	1.71	1.08	0.77	2.84	2.66	1.83	1.13	0.80
		50	30	1.87	1.81	1.45	1.04	0.80	2.09	2.01	1.58	1.10	0.84
		50	10	2.50	2.40	1.81	1.21	0.89	2.80	2.66	1.95	1.28	0.93
		0	20	2.01	1.95	1.63	1.23	0.97	2.25	2.18	1.79	1.32	1.03
		0	10	2.43	2.35	1.90	1.38	1.06	2.71	2.62	2.07	1.47	1.12
		−50	20	1.94	1.91	1.68	1.36	1.13	2.19	2.14	1.86	1.47	1.20
		−50	10	2.37	2.31	1.99	1.55	1.26	2.65	2.58	2.18	1.67	1.33
45° Slope	Up ↗	90	10	2.92	2.73	1.86	1.14	0.80	3.18	2.96	1.97	1.18	0.82
		50	30	2.14	2.06	1.61	1.12	0.84	2.26	2.17	1.67	1.15	0.86
		50	10	2.88	2.74	1.99	1.29	0.94	3.12	2.95	2.10	1.34	0.96
		0	20	2.30	2.23	1.82	1.34	1.04	2.42	2.35	1.90	1.38	1.06
		0	10	2.79	2.69	2.12	1.49	1.13	2.98	2.87	2.23	1.54	1.16
		−50	20	2.22	2.17	1.88	1.49	1.21	2.34	2.29	1.97	1.54	1.25
		−50	10	2.71	2.64	2.23	1.69	1.35	2.87	2.79	2.33	1.75	1.39
Vertical	Horiz. →	90	10	3.99	3.66	2.25	1.27	0.87	3.69	3.40	2.15	1.24	0.85
		50	30	2.58	2.46	1.84	1.23	0.90	2.67	2.55	1.89	1.25	0.91
		50	10	3.79	3.55	2.39	1.45	1.02	3.63	3.40	2.32	1.42	1.01
		0	20	2.76	2.66	2.10	1.48	1.12	2.88	2.78	2.17	1.51	1.14
		0	10	3.51	3.35	2.51	1.67	1.23	3.49	3.33	2.50	1.67	1.23
		−50	20	2.64	2.58	2.18	1.66	1.33	2.82	2.75	2.30	1.73	1.37
		−50	10	3.31	3.21	2.62	1.91	1.48	3.40	3.30	2.67	1.94	1.50
45° Slope	Down ↘	90	10	5.07	4.55	2.56	1.36	0.91	4.81	4.33	2.49	1.34	0.90
		50	30	3.58	3.36	2.31	1.42	1.00	3.51	3.30	2.28	1.40	1.00
		50	10	5.10	4.66	2.85	1.60	1.09	4.74	4.36	2.73	1.57	1.08
		0	20	3.85	3.66	2.68	1.74	1.27	3.81	3.63	2.66	1.74	1.27
		0	10	4.92	4.62	3.16	1.94	1.37	4.59	4.32	3.02	1.88	1.34
		−50	20	3.62	3.50	2.80	2.01	1.54	3.77	3.64	2.90	2.05	1.57
		−50	10	4.67	4.47	3.40	2.29	1.70	4.50	4.32	3.31	2.25	1.68
Horiz.	Down ↓	90	10	6.09	5.35	2.79	1.43	0.94	10.07	8.19	3.41	1.57	1.00
		50	30	6.27	5.63	3.18	1.70	1.14	9.60	8.17	3.86	1.88	1.22
		50	10	6.61	5.90	3.27	1.73	1.15	11.15	9.27	4.09	1.93	1.24
		0	20	7.03	6.43	3.91	2.19	1.49	10.90	9.52	4.87	2.47	1.62
		0	10	7.31	6.66	4.00	2.22	1.51	11.97	10.32	5.08	2.52	1.64
		−50	20	7.73	7.20	4.77	2.85	1.99	11.64	10.49	6.02	3.25	2.18
		−50	10	8.09	7.52	4.91	2.89	2.01	12.98	11.56	6.36	3.34	2.22

[a] See Chapter 25. Thermal resistance values were determined from $R = 1/C$, where $C = h_c + \varepsilon_{eff}\, h_r$, h_c is conduction/convection coefficient, $\varepsilon_{eff}\, h_r$ is radiation coefficient $\approx 0.0068\varepsilon_{eff}[(t_m + 460)/100]^3$, and t_m is mean temperature of air space. Values for h_c were determined from data developed by Robinson et al. (1954). Equations (5) to (7) in Yarbrough (1983) show data in this table in analytic form. For extrapolation from this table to air spaces less than 0.5 in. (e.g., insulating window glass), assume $h_c = 0.159(1 + 0.0016t_m)/l$, where l is air space thickness in in., and h_c is heat transfer through air space only.

[b] Values based on data presented by Robinson et al. (1954). (Also see Chapter 4, Tables 5 and 6, and Chapter 33). Values apply for ideal conditions (i.e., air spaces of uniform thickness bounded by plane, smooth, parallel surfaces with no air leakage to or from the space). For greater accuracy, use overall U-factors determined through calibrated hot box (ASTM *Standard* C976) or guarded hot box (ASTM *Standard* C236) testing. Thermal resistance values for multiple air spaces must be based on careful estimates of mean temperature differences for each air space.

[c] A single resistance value cannot account for multiple air spaces; each air space requires a separate resistance calculation that applies only for established boundary conditions. Resistances of horizontal spaces with heat flow downward are substantially independent of temperature difference.

[d] Interpolation is permissible for other values of mean temperature, temperature difference, and effective emittance ε_{eff}. Interpolation and moderate extrapolation for air spaces greater than 3.5 in. are also permissible.

[e] Effective emittance ε_{eff} of air space is given by $1/\varepsilon_{eff} = 1/\varepsilon_1 + 1/\varepsilon_2 - 1$, where ε_1 and ε_2 are emittances of surfaces of air space (see Table 2).

Basic Materials

Thermal insulation normally consists of the following basic materials and composites:

- Inorganic, fibrous, or cellular materials such as glass, rock, or slag wool
- Calcium silicate, bonded perlite, vermiculite, and ceramic products (asbestos was also used, but its use has been discouraged or banned for several years; use caution if it is encountered in existing buildings)
- Organic fibrous materials such as cellulose, cotton, wool, wood, pulp, cane, or synthetic fibers, and organic cellular materials such as cork, foamed rubber, polystyrene, polyurethane, and other polymers
- Metallic or metallized organic reflective membranes, which must face an air-filled, gas-filled, or evacuated space to be effective

Physical Structure and Form

Physical forms of building insulation include the following:

Loose-fill insulation consists of fibers, powders, granules, or nodules, usually poured or blown into walls or other spaces. **Insulating cement** is a loose material that is mixed with water or a suitable binder to obtain plasticity and adhesion. It is troweled or blown wet on a surface and dried in place. Both loose fill and insulating cement are suited for covering irregular spaces.

Flexible and **semirigid insulation** consists of organic and inorganic materials with and without binders and with varying degrees of compressibility and flexibility. This insulation is generally available as blanket, batt, or felt, and in either sheets or rolls. Coverings and facings may be fastened to one or both sides and serve as reinforcing, airflow or vapor retarders (or both), reflective surfaces, or surface finishes. These coverings include combinations of laminated foil, glass, cloth or plastics and paper, or wire mesh. Although standard sizes are generally used, thickness and shape of insulation can be any convenient dimension.

Rigid materials are available in rectangular blocks, boards, or sheets, which are preformed during manufacture to standard lengths, widths, and thickness.

Reflective materials are available in sheets and rolls of single-layer or multilayer construction and in preformed shapes with integral air spaces.

Formed-in-place insulations are available as liquid components or expandable pellets that can be poured, frothed, or sprayed in place to form rigid or semirigid foam insulation. Fibrous materials mixed with liquid binders can also be sprayed in place; in some products, the binder is also a foam.

Accessories for thermal insulation include mechanical and adhesive fasteners, exterior and interior finishes, vapor- and airflow-retarding coatings, sealants, lagging adhesives, membranes, and flashing compounds. ASTM *Standard* C168 defines terms related to thermal insulating materials.

Apparent Thermal Conductivity

A low apparent thermal conductivity is the primary property of a thermal insulation, but selecting a material may also involve secondary criteria (e.g., resiliency or rigidity, acoustical energy absorption, water vapor permeability, airflow resistance, fire hazard and fire resistance, ease of application, applied cost, health and safety aspects, or other parameters), which can affect the choice among materials that have almost equal thermal performance.

Thermal conductivity k is a property of a homogeneous, nonporous material. Most thermal insulation is porous and consists of combinations of solid matter with small voids, which comprise 90% or more of the volume. Heat transmission is therefore a combination of gas and solid conduction, radiation, and convection, and is affected by factors such as length of heat flow paths, temperature, temperature difference, and environmental conditions. In fact, a wide variety of physical, environmental, application, and, in some cases, aging factors affect the thermal performance of insulation. In some materials with low thermal conductivity (e.g., opacified silica aerogel, corkboard), heat transfer is almost purely conductive.

Although heat transmission characteristics are usually determined by measuring thermal conductivity, this property does not strictly apply to thermal insulation. A particular sample of a material has a unique value of thermal conductivity for a particular set of conditions. This value may not be representative of the material at other conditions and should be called **apparent thermal conductivity**. For details, refer to ASTM *Standards* C168, C177, C335, C518, C976, and C1045.

Reflective insulation reduces radiant heat transfer because the surfaces have high reflectance and low emittance values. Conventional calculation methods ascribe the radiative properties to the associated air cavity, rather than to the insulation layer, to avoid incorrectly ascribing the benefits of reflective insulation that does not face an air cavity. Tables 1 and 2 give typical design values for air cavities faced with reflective layers. Multiple layers of reflective materials and smooth and parallel sealed air spaces increase overall thermal resistance. Air exchange and movement must be inhibited, however, or the reduction in radiative heat transfer is overshadowed by increased convection.

Mass-type insulation can be combined with reflective surfaces and air spaces to increase thermal resistance. However, each design must be evaluated, because maximum thermal performance of these systems depends on factors such as condition of the insulation, shape and form of construction, means to avoid air leakage and movement, and condition and aging characteristics of installed reflective surfaces.

Design values of apparent thermal conductivity, thermal conductance, and thermal resistance for most common insulation materials are listed in Table 4. These values have been selected as typical and useful for engineering calculations. Test results of insulation under appropriate conditions give values for that particular case.

Insulation's form and physical structure, environment, and application conditions can affect its apparent thermal conductivity. Form and physical structure vary with the basic material and manufacturing process. Typical variations include density, cell size, diameter and arrangement of fibers or particles, degree and extent of bonding materials, transparency to thermal radiation, and type and pressure of gas within the insulation.

Figure 2 illustrates the variation with density of the apparent thermal conductivity at one mean temperature for a number of insulation materials used in building envelopes. For most mass-type insulation, there is a minimum that depends on the type and form of the material, temperature, and direction of heat flow. For fibrous materials, the values of density at which the minimum occurs increase as both the fiber diameter (or cell size) and the mean temperature increase. These effects are shown in Figures 3 (Lotz 1969) and 4.

Other structural factors that affect thermal performance include compaction and settling of insulation, air permeability, type and amount of binder used, additives that may influence the bond or contact between fibers or particles, and type and form of radiation transfer inhibitor, if used. In cellular materials, most factors that influence strength also control thermal conductivity: size, shape, and orientation of the cells, and thickness of the cell walls. However, gas contained in the cells and radiation characteristics of cell surfaces also influence the effective conductivity.

Density changes caused by compaction affect the apparent thermal conductivity of insulation powders. Insulating concretes made from lightweight aggregates can be produced in a wide range of densities, with corresponding thermal conductivity. Fibrous insulation reaches a minimum conductivity when fibers are uniformly spaced and perpendicular to the direction of heat flow. Generally, a decrease in fiber diameter lowers conductivity for the same density

Table 4 Typical Thermal Properties of Common Building and Insulating Materials: Design Values[a]

Description	Density, lb/ft³	Conductivity[b] k, Btu·in/h·ft²·°F	Resistance R, h·ft²·°F/Btu	Specific Heat, Btu/lb·°F	Reference[n]
Building Board and Siding					
Board					
Asbestos/cement board	120	4	—	0.24	Nottage (1947)
Cement board	72	1.7	—	0.2	Kumaran (2002)
Fiber/cement board	88	1.7	—	0.2	Kumaran (2002)
	63	1.3	—	0.2	Kumaran (1996)
	25	0.5	—	0.45	Kumaran (1996)
	19	0.4	—	0.45	Kumaran (1996)
Gypsum or plaster board	40	1.1	—	0.27	Kumaran (2002)
Oriented strand board (OSB) 7/16 in.	41	—	0.62	0.45	Kumaran (2002)
1/2 in.	41	—	0.68	0.45	Kumaran (2002)
Plywood (douglas fir) 1/2 in.	29	—	0.79	0.45	Kumaran (2002)
5/8 in.	34	—	0.85	0.45	Kumaran (2002)
Plywood/wood panels 3/4 in.	28	—	1.08	0.45	Kumaran (2002)
Vegetable fiber board				—	
Sheathing, regular density[e] 1/2 in.	18	—	1.32	0.31	Lewis (1967)
intermediate density[e] 1/2 in.	22	—	1.09	0.31	Lewis (1967)
Nail-base sheathing[e] 1/2 in.	25	—	1.06	0.31	
Shingle backer 3/8 in.	18	—	0.94	0.3	
Sound-deadening board 1/2 in.	15	—	1.35	0.3	
Tile and lay-in panels, plain or acoustic	18	0.4	—	0.14	
Laminated paperboard	30	0.5	—	0.33	Lewis (1967)
Homogeneous board from repulped paper	30	0.5	—	0.28	
Hardboard[e]					
medium density	50	0.73	—	0.31	Lewis (1967)
high density, service-tempered grade and service grade	55	0.82	—	0.32	Lewis (1967)
high density, standard-tempered grade	63	1	—	0.32	Lewis (1967)
Particleboard[e]					
low density	37	0.71	—	0.31	Lewis (1967)
medium density	50	0.94	—	0.31	Lewis (1967)
high density	62	0.5	0.85	—	Lewis (1967)
underlayment 5/8 in.	40	—	0.82	0.29	Lewis (1967)
Waferboard	37	0.63	—	0.45	Kumaran (1996)
Shingles					
Asbestos/cement	120	—	0.21	—	
Wood, 16 in., 7 1/2 in. exposure	—	—	0.87	0.31	
Wood, double, 16 in., 12 in. exposure	—	—	1.19	0.28	
Wood, plus ins. backer board 5/16 in.	—	—	1.4	0.31	
Siding				—	
Asbestos/cement, lapped 1/4 in.	—	—	0.21	0.24	
Asphalt roll siding	—	—	0.15	0.35	
Siding					
Asphalt insulating siding (1/2 in. bed)	—	—	1.46	0.35	
Hardboard siding 7/16 in.	—	—	0.67	0.28	
Wood, drop, 8 in. 1 in.	—	—	0.79	0.28	
Wood, bevel					
8 in., lapped 1/2 in.	—	—	0.81	0.28	
10 in., lapped 3/4 in.	—	—	1.05	0.28	
Wood, plywood, 3/8 in., lapped	—	—	0.59	0.29	
Aluminum, steel, or vinyl,[j, k] over sheathing				—	
hollow-backed	—	—	0.62	0.29[k]	
insulating-board-backed				—	
3/8 in.	—	—	1.82	0.32	
foil-backed 3/8 in.	—	—	2.96	—	
Architectural (soda-lime float) glass	158	6.9	—	0.2	
Building Membrane					
Vapor-permeable felt	—	—	0.06	—	
Vapor: seal, 2 layers of mopped 15 lb felt	—	—	0.12	—	
Vapor: seal, plastic film	—	—	Negligible	—	

Table 4 Typical Thermal Properties of Common Building and Insulating Materials: Design Values[a] (*Continued*)

Description	Density, lb/ft	Conductivity[b] *k*, Btu·in/h·ft²·°F	Resistance *R*, h·ft²·°F/Btu	Specific Heat, Btu/lb·°F	Reference[n]
Finish Flooring Materials					
Carpet and rebounded urethane pad 3/4 in.	7	—	2.38	—	NIST (2000)
Carpet and rubber pad (one-piece) 3/8 in.	20	—	0.68	—	NIST (2000)
Pile carpet with rubber pad 3/8 to 1/2 in.	18	—	1.59	—	NIST (2000)
Linoleum/cork tile 1/4 in.	29	—	0.51	—	NIST (2000)
PVC/Rubber floor covering	—	2.8	—	—	CIBSE (2006)
Rubber tile 1.0 in.	119	—	0.34	—	NIST (2000)
Terrazzo 1.0 in.	—	—	0.08	0.19	
Insulating Materials					
Blanket and batt[c,d]					
Glass-fiber batts 3 to 3 1/2 in.	0.6 to 0.9	0.3	—	0.2	Kumaran (2002)
6 in.	0.5 to 0.8	—	—	0.2	Kumaran (2002)
Mineral fiber 5 1/2 in.	2	0.2	—	0.2	Kumaran (1996)
Mineral wool, felted	1 to 3	0.3	—	—	CIBSE (2006), NIST (2000)
	4.1 to 8.1	0.2	—	—	NIST (2000)
Slag wool	3.1 to 11.9	0.3	—	—	Raznjevic (1976)
	16	0.3	—	—	Raznjevic (1976)
	19	0.3	—	—	Raznjevic (1976)
	22	0.3	—	—	Raznjevic (1976)
	25	0.3	—	—	Raznjevic (1976)
Board and slabs					
Cellular glass	8.0	0.33	—	0.18	(Manufacturer)
Cement fiber slabs, shredded wood with Portland cement binder	25 to 27.0	0.50 to 0.53	—	—	
with magnesia oxysulfide binder	22.0	0.57	—	0.31	
Glass fiber board	10	0.22 to 0.28	—	0.2	Kumaran (1996)
Expanded rubber (rigid)	4	0.2	—	0.4	Nottage (1947)
Expanded polystyrene extruded (smooth skin)	1.6 to 2.5	0.15 to 0.21	—	0.35	Kumaran (1996)
Expanded polystyrene, molded beads	0.9 to 1.6	0.22 to 0.27	—	0.35	Kumaran (1996)
Mineral fiberboard, wet felted	10	0.3	—	0.2	Kumaran (1996)
core or roof insulation	16 to 17	0.34	—	—	
acoustical tile[g]	18.0	—	—	0.19	
	21.0	0.37	—	—	
wet-molded, acoustical tile[g]	23.0	0.42	—	0.14	
Perlite board	10	0.4	—	—	Kumaran (1996)
Polyisocyanurate, aged					
unfaced	1.6 to 2.2	0.14 to 0.19	—	—	Kumaran (2002)
with facers	4	0.1	—	0.35	Kumaran (1996)
Phenolic foam board with facers, aged	4	0.1	—	—	Kumaran (1996)
Loose fill					
Cellulosic (milled paper or wood pulp)	2.2 to 3.1	0.27 to 0.31	—	0.33	NIST (2000), Kumaran (1996)
Perlite, expanded	1.9 to 4.1	0.27 to 0.31	—	0.26	(Manufacturer)
	4.1 to 7.5	0.31 to 0.36	—	—	(Manufacturer)
	7.5 to 11.2	0.36 to 0.42	—	—	(Manufacturer)
Mineral fiber (rock, slag, or glass)[d]					
approx. 3 3/4 to 5 in.	0.6 to 2.0	—	11.0	0.17	
approx. 6 1/2 to 8 3/4 in.	0.6 to 2.0	—	19.0	—	
approx. 7 1/2 to 10 in.	0.6 to 2.0	—	22.0	—	
approx. 10 1/4 to 13 3/4 in.	0.6 to 2.0	—	30.0	—	
approx. 3 1/2 in. (closed sidewall application)	2.0 to 3.5	—	12.0 to 14.0	—	
Vermiculite, exfoliated	7.0 to 8.2	0.47	—	0.32	Sabine et al. (1975)
	4.0 to 6.0	0.44	—	—	(Manufacturer)
Spray-applied					
Cellulosic fiber	3.4 to 5.9	0.29 to 0.34	—	—	Yarbrough et al. (1987)
Glass fiber	3.4 to 4.4	0.26 to 0.27	—	—	Yarbrough et al. (1987)
Polyurethane foam (low density)	0.4 to 0.5	0.3	—	0.35	Kumaran (2002)
	3	0.2	—	0.35	Kumaran (2002)
aged and dry 1 1/2 in.	2	—	9.09	0.35	Kumaran (1996)
2 in.	3	—	10.9	0.35	Kumaran (1996)
4 1/2 in.	2	—	20.95	—	Kumaran (1996)
Ureaformaldehyde foam, dry	0.5 to 1.2	0.21 to 0.22	—	—	CIBSE (2006)
Metals					
(See Chapter 33, Table 3)					

Table 4 Typical Thermal Properties of Common Building and Insulating Materials: Design Values[a] (*Continued*)

Description	Density, lb/ft	Conductivity[b] *k*, Btu·in/h·ft^2·°F	Resistance *R*, h·ft^2·°F/Btu	Specific Heat, Btu/lb·°F	Reference[n]
Roofing					
Asbestos/cement shingles	120	—	0.21	0.24	
Asphalt (bitumen with inert fill)	100	3	—	—	CIBSE (2006)
	119	4	—	—	CIBSE (2006)
	144	8	—	—	CIBSE (2006)
Asphalt roll roofing	70	—	0.15	0.36	
Asphalt shingles	70	—	0.44	0.3	
Built-up roofing 3/8 in.	70	—	0.33	0.35	
Mastic asphalt (heavy, 20% grit)	59	1.3	—	—	CIBSE (2006)
Reed thatch	17	0.6	—	—	CIBSE (2006)
Roofing felt	141	8.3	—	—	CIBSE (2006)
Slate 1/2 in.	—	—	0.05	0.3	
Straw thatch	15	0.5	—	—	CIBSE (2006)
Wood shingles, plain and plastic-film-faced	—	—	0.94	0.31	
Plastering Materials					
Cement plaster, sand aggregate	116	5.0	—	0.2	
Sand aggregate					
3/8 in.	—	—	0.08	0.2	
3/4 in.	—	—	0.15	0.2	
Gypsum plaster	70	2.6	—	—	CIBSE (2006)
	80	3.2	—	—	CIBSE (2006)
Lightweight aggregate					
1/2 in.	45	—	0.32	—	
5/8 in.	45	—	0.39	—	
on metal lath 3/4 in.	—	—	0.47	—	
Perlite aggregate	45	1.5	—	0.32	
Sand aggregate	105	5.6	—	0.2	
on metal lath 3/4 in.	—	—	0.13	—	
Vermiculite aggregate	30	1	—	—	CIBSE (2006)
	38	1.4	—	—	CIBSE (2006)
	45	1.7	—	—	CIBSE (2006)
	53	1.8	—	—	CIBSE (2006)
	60	2.1	—	—	CIBSE (2006)
Perlite plaster	25	0.6	—	—	CIBSE (2006)
	38	1.3	—	—	CIBSE (2006)
Pulpboard or paper plaster	38	0.5	—	—	CIBSE (2006)
Sand/cement plaster, conditioned	98	4.4	—	—	CIBSE (2006)
Sand/cement/lime plaster, conditioned	90	3.3	—	—	CIBSE (2006)
Sand/gypsum (3:1) plaster, conditioned	97	4.5	—	—	CIBSE (2006)
Masonry Materials					
Masonry units					
Brick, fired clay	150	8.4 to 10.2	—	—	Valore (1988)
	140	7.4 to 9.0	—	—	Valore (1988)
	130	6.4 to 7.8	—	—	Valore (1988)
	120	5.6 to 6.8	—	0.19	Valore (1988)
	110	4.9 to 5.9	—	—	Valore (1988)
	100	4.2 to 5.1	—	—	Valore (1988)
	90	3.6 to 4.3	—	—	Valore (1988)
	80	3.0 to 3.7	—	—	Valore (1988)
	70	2.5 to 3.1	—	—	Valore (1988)
Clay tile, hollow					
1 cell deep 3 in.	—	—	0.80	0.21	Rowley (1937)
4 in.	—	—	1.11	—	Rowley (1937)
2 cells deep 6 in.	—	—	1.52	—	Rowley (1937)
8 in.	—	—	1.85	—	Rowley (1937)
10 in.	—	—	2.22	—	Rowley (1937)
3 cells deep 12 in.	—	—	2.50	—	Rowley (1937)
Lightweight brick	50	1.4	—	—	Kumaran (1996)
	48	1.5	—	—	Kumaran (1996)
Concrete blocks[h, i]					
Limestone aggregate					
8 in., 36 lb, 138 lb/ft^3 concrete, 2 cores	—	—	—	—	
with perlite-filled cores	—	—	2.1	—	Valore (1988)
12 in., 55 lb, 138 lb/ft^3 concrete, 2 cores	—		—	—	
with perlite-filled cores	—	—	3.7	—	Valore (1988)

Table 4 Typical Thermal Properties of Common Building and Insulating Materials: Design Values[a] (*Continued*)

Description	Density, lb/ft	Conductivity[b] k, Btu·in/h·ft^2·°F	Resistance R, h·ft^2·°F/Btu	Specific Heat, Btu/lb·°F	Reference[n]
Normal-weight aggregate (sand and gravel)					
8 in., 33 to 36 lb, 126 to 136 lb/ft^3 concrete, 2 or 3 cores	—	—	1.11 to 0.97	0.22	Van Geem (1985)
with perlite-filled cores	—	—	2.0	—	Van Geem (1985)
with vermiculite-filled cores	—	—	1.92 to 1.37	—	Valore (1988)
12 in., 50 lb, 125 lb/ft^3 concrete, 2 cores	—	—	1.23	0.22	Valore (1988)
Medium-weight aggregate (combinations of normal and lightweight aggregate)					
8 in., 26 to 29 lb, 97 to 112 lb/ft^3					
concrete, 2 or 3 cores	—	—	1.71 to 1.28	—	Van Geem (1985)
with perlite-filled cores	—	—	3.7 to 2.3	—	Van Geem (1985)
with vermiculite-filled cores	—	—	3.3	—	Van Geem (1985)
with molded-EPS-filled (beads) cores	—	—	3.2	—	Van Geem (1985)
with molded EPS inserts in cores	—	—	2.7	—	Van Geem (1985)
Lightweight aggregate (expanded shale, clay, slate or slag, pumice)					
6 in., 16 to 17 lb, 85 to 87 lb/ft^3					
concrete, 2 or 3 cores	—	—	1.93 to 1.65	—	Van Geem (1985)
with perlite-filled cores	—	—	4.2	—	Van Geem (1985)
with vermiculite-filled cores	—	—	3.0	—	Van Geem (1985)
8 in., 19 to 22 lb, 72 to 86 lb/ft^3 concrete	—	—	3.2 to 1.90	0.21	Van Geem (1985)
with perlite-filled cores	—	—	6.8 to 4.4	—	Van Geem (1985)
with vermiculite-filled cores	—	—	5.3 to 3.9	—	Shu et al. (1979)
with molded-EPS-filled (beads) cores	—	—	4.8	—	Shu et al. (1979)
with UF foam-filled cores	—	—	4.5	—	Shu et al. (1979)
with molded EPS inserts in cores	—	—	3.5	—	Shu et al. (1979)
12 in., 32 to 36 lb, 80 to 90 lb/ft^3,					
concrete, 2 or 3 cores	—	—	2.6 to 2.3	—	Van Geem (1985)
with perlite-filled cores	—	—	9.2 to 6.3	—	Van Geem (1985)
with vermiculite-filled cores	—	—	5.8	—	Valore (1988)
Stone, lime, or sand	180	72	—	—	Valore (1988)
Quartzitic and sandstone	160	43	—	—	Valore (1988)
	140	24	—	—	Valore (1988)
	120	13	—	0.21	Valore (1988)
Calcitic, dolomitic, limestone, marble, and granite	180	30	—	—	Valore (1988)
	160	22	—	—	Valore (1988)
	140	16	—	—	Valore (1988)
	120	11	—	0.21	Valore (1988)
	100	8	—	—	Valore (1988)
Gypsum partition tile					
3 by 12 by 30 in., solid	—	—	1.26	0.19	Rowley (1937)
4 cells	—	—	1.35	—	Rowley (1937)
4 by 12 by 30 in., 3 cells	—	—	1.67	—	Rowley (1937)
Limestone	150	4	—	0.2	Kumaran (2002)
	163	6.4	—	0.2	Kumaran (2002)
Concretes[i]					
Sand and gravel or stone aggregate concretes (concretes with >50% quartz or quartzite sand have conductivities in higher end of range)	150	10.0 to 20.0	—	—	Valore (1988)
	140	9.0 to 18.0	—	0.19 to 0.24	Valore (1988)
	130	7.0 to 13.0	—	—	Valore (1988)
Lightweight aggregate or limestone concretes	120	6.4 to 9.1	—	—	Valore (1988)
Expanded shale, clay, or slate; expanded slags; cinders; pumice (with density up to 100 lb/ft^3); scoria (sanded concretes have conductivities in higher end of range)	100	4.7 to 6.2	—	0.2	Valore (1988)
	80	3.3 to 4.1	—	0.2	Valore (1988)
	60	2.1 to 2.5	—	—	Valore (1988)
	40	1.3	—	—	Valore (1988)
Gypsum/fiber concrete (87.5% gypsum, 12.5% wood chips)	51	1.66	—	0.2	Rowley (1937)
Cement/lime, mortar, and stucco	120	9.7	—	—	Valore (1988)
	100	6.7	—	—	Valore (1988)
	80	4.5	—	—	Valore (1988)
Perlite, vermiculite, and polystyrene beads	50	1.8 to 1.9	—	—	Valore (1988)
	40	1.4 to 1.5	—	0.15 to 0.23	Valore (1988)
	30	1.1	—	—	Valore (1988)

Table 4 Typical Thermal Properties of Common Building and Insulating Materials: Design Values[a] (*Continued*)

Description	Density, lb/ft	Conductivity[b] k, Btu·in/h·ft^2·°F	Resistance R, h·ft^2·°F/Btu	Specific Heat, Btu/lb·°F	Reference[n]
	20	0.8	—	—	Valore (1988)
Foam concretes	120	5.4	—	—	Valore (1988)
	100	4.1	—	—	Valore (1988)
	80	3.0	—	—	Valore (1988)
	70	2.5	—	—	Valore (1988)
Foam concretes and cellular concretes	60	2.1	—	—	Valore (1988)
	40	1.4	—	—	Valore (1988)
	20	0.8	—	—	Valore (1988)
Aerated concrete (oven-dried)	27 to 50	1.4	—	0.2	Kumaran (1996)
Polystyrene concrete (oven-dried)	16 to 50	2.6	—	0.2	Kumaran (1996)
Polymer concrete	122	11.4	—	—	Kumaran (1996)
	138	7.1	—	—	Kumaran (1996)
Polymer cement	117	5.4	—	—	Kumaran (1996)
Slag concrete	60	1.5	—	—	Touloukian et al (1970)
	80	2.2	—	—	Touloukian et al. (1970)
	100	3	—	—	Touloukian et al. (1970)
	125	8.5	—	—	Touloukian et al. (1970)
Woods (12% moisture content)[l]					
Hardwoods	—	—	—	0.39[m]	Wilkes (1979)
Oak	41.2 to 46.8	1.12 to 1.25	—	—	Cardenas
Birch	42.6 to 45.4	1.16 to 1.22	—	—	Cardenas
Maple	39.8 to 44.0	1.09 to 1.19	—	—	Cardenas
Ash	38.4 to 41.9	1.06 to 1.14	—	—	Cardenas
Softwoods	—	—	—	0.39[m]	Wilkes (1979)
Southern pine	35.6 to 41.2	1.00 to 1.12	—	—	Cardenas
Southern yellow pine	31	0.9	—	—	Kumaran (2002)
Eastern white pine	25	0.7	—	—	Kumaran (2002)
Douglas fir/larch	33.5 to 36.3	0.95 to 1.01	—	—	Cardenas and Bible (1987)
Southern cypress	31.4 to 32.1	0.90 to 0.92	—	—	Cardenas and Bible (1987)
Hem/fir, spruce/pine/fir	24.5 to 31.4	0.74 to 0.90	—	—	Cardenas and Bible (1987)
Spruce	25	0.6	—	—	Kumaran (2002)
Western red cedar	22	0.6	—	—	Kumaran (2002)
West coast woods, cedars	21.7 to 31.4	0.68 to 0.90	—	—	Cardenas and Bible (1987)
Eastern white cedar	23	0.7	—	—	Kumaran (2002)
California redwood	24.5 to 28.0	0.74 to 0.82	—	—	Cardenas and Bible (1987)
Pine (oven-dried)	23	0.64	—	0.45	Kumaran (1996)
Spruce (oven-dried)	25	0.69	—	0.45	Kumaran (1996)

Notes for Table 4

[a] Values are for mean temperature of 75°F. Representative values for dry materials are intended as design (not specification) values for materials in normal use. Thermal values of insulating materials may differ from design values depending on in-situ properties (e.g., density and moisture content, orientation, etc.) and manufacturing variability. For properties of specific product, use values supplied by manufacturer or unbiased tests.

[b] Symbol λ also used to represent thermal conductivity.

[c] Does not include paper backing and facing, if any. Where insulation forms boundary (reflective or otherwise) of airspace, see Tables 2 and 3 for insulating value of airspace with appropriate effective emittance and temperature conditions of space.

[d] Conductivity varies with fiber diameter (see Chapter 25). Batt, blanket, and loose-fill mineral fiber insulations are manufactured to achieve specified R-values, the most common of which are listed in the table. Because of differences in manufacturing processes and materials, the product thicknesses, densities, and thermal conductivities vary over considerable ranges for a specified R-value.

[e] Values are for aged products with gas-impermeable facers on the two major surfaces. An aluminum foil facer of 0.001 in. thickness or greater is generally considered impermeable to gases. For change in conductivity with age of expanded polyisocyanurate, see SPI Bulletin U108.

[f] Cellular phenolic insulation may no longer be manufactured. Thermal conductivity and resistance values do not represent aged insulation, which may have higher thermal conductivity and lower thermal resistance.

[g] Insulating values of acoustical tile vary, depending on density of board and on type, size, and depth of perforations.

[h] Values for fully grouted block may be approximated using values for concrete with similar unit density.

[i] Values for concrete block and concrete are at moisture contents representative of normal use.

[j] Values for metal or vinyl siding applied over flat surfaces vary widely, depending on ventilation of the airspace beneath the siding; whether airspace is reflective or nonreflective; and on thickness, type, and application of insulating backing-board used. Values are averages for use as design guides, and were obtained from several guarded hot box tests (ASTM *Standard* C236) or calibrated hot box (ASTM *Standard* C976) on hollow-backed types and types made using backing of wood fiber, foamed plastic, and glass fiber. Departures of ±50% or more from these values may occur.

[k] Vinyl specific heat = 0.25 Btu/lb·°F

[l] See Adams (1971), MacLean (1941), and Wilkes (1979). Conductivity values listed are for heat transfer across the grain. Thermal conductivity of wood varies linearly with density, and density ranges listed are those normally found for wood species given. If density of wood species is not known, use mean conductivity value. For extrapolation to other moisture contents, the following empirical equation developed by Wilkes (1979) may be used:

$$k = 0.1791 + \frac{(1.874 \times 10^{-2} + 5.753 \times 10^{-4} M)\rho}{1 + 0.01M}$$

where ρ is density of moist wood in lb/ft^3, and M is moisture content in percent.

[m] From Wilkes (1979), an empirical equation for specific heat of moist wood at 75°F is as follows:

$$c_p = \frac{(0.299 + 0.01M)}{(1 + 0.01M)} + \Delta c_p$$

where Δc_p accounts for heat of sorption and is denoted by

$$\Delta c_p = M(1.921 \times 10^{-3} - 3.168 \times 10^{-5} M)$$

where M is moisture content in percent by mass.

[n] Blank space in reference column indicates historical values from previous volumes of *ASHRAE Handbook*. Source of information could not be determined.

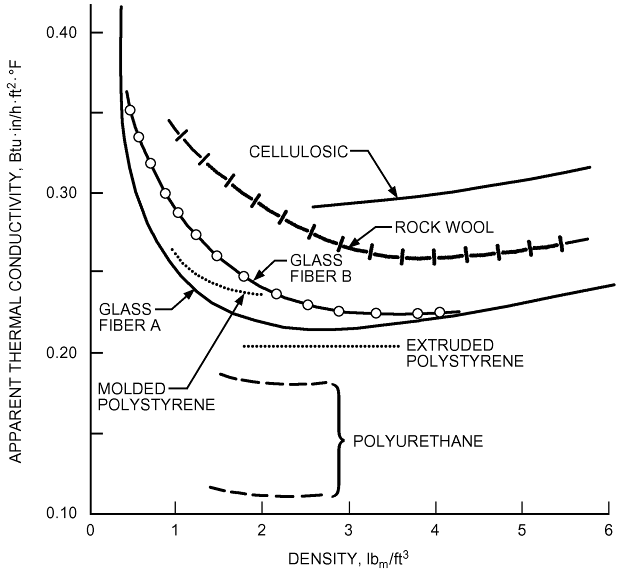

Fig. 2 Apparent Thermal Conductivity Versus Density of Several Thermal Insulations Used as Building Insulations

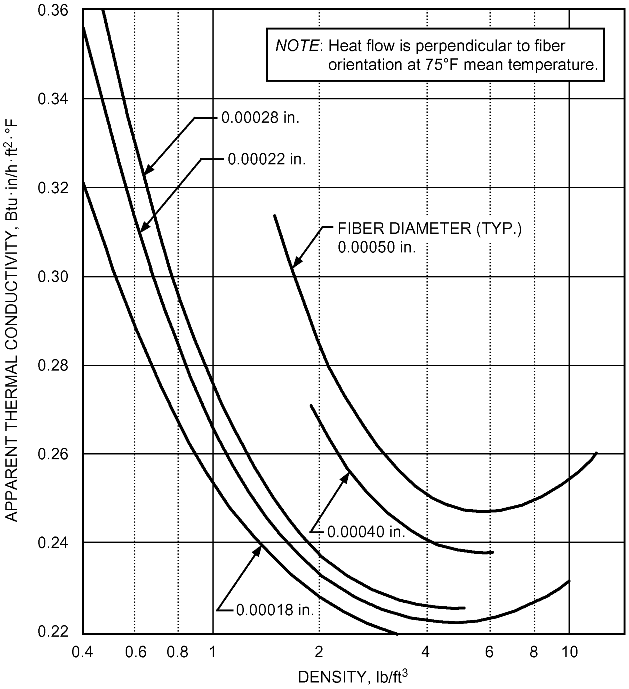

Fig. 3 Variation of Apparent Thermal Conductivity with Fiber Diameter and Density

(Figure 4). For cellular insulation, a specific combination of cell size, density, and gas composition produces optimum thermal conductivity.

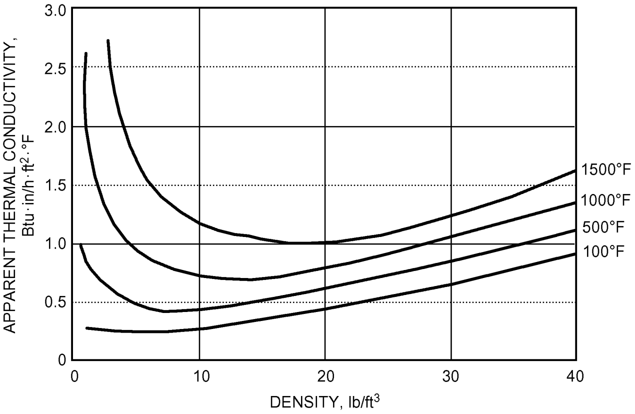

Fig. 4 Typical Variation of Apparent Thermal Conductivity with Mean Temperature and Density for Fibrous Insulations

At temperatures below 400 to 570°F, a large portion of heat transfer occurs by conduction through air or another gas in the insulation (Lander 1955; Rowley et al. 1952; Simons 1955; Verschoor and Greebler 1952). The overall heat transfer can be closely approximated by supposition of gas conduction with all other mechanisms, each determined separately. If the gas in the insulation is replaced by another gas with a different thermal conductivity, the apparent thermal conductivity changes by an amount approximately equal to the difference in conductivity of the two gases. For example, replacing air with a fluorinated hydrocarbon (HFC) can lower the apparent thermal conductivity of insulation by as much as 50%.

Fluorocarbon-expanded cellular plastic foams with a high proportion (greater than 90%) of closed cells retain the fluorocarbon for extended periods of time. Newly produced, they have apparent thermal conductivities of approximately 0.11 Btu·in/h·ft²·°F at 75°F, but this value increases with time as air diffuses into the cells and the fluorocarbon gas gradually dissolves in the polymer or diffuses out. Diffusion rates and increase in apparent thermal conductivity depend on several factors, including permeance of cell walls to the gases involved, foam age, temperature, geometry of the insulation (thickness), and integrity of the surface protection provided. Brandreth (1986) and Tye (1988) showed that aging of polyurethane and polyisocyanurate is reasonably well understood analytically and confirmed experimentally. The dominant parameters for minimum aging are as follows:

- Closed-cell content >90%, preferably >95%
- Small, uniform cell diameter <<0.04 in., with larger proportion of polymer in windows between cells
- Small anisotropy in cell structure
- High density
- Increased thickness
- High initial pressure of fluorocarbon blowing agent in cell
- Polymer highly resistant to gas diffusion and solubility
- Polymer distributed evenly in struts and windows of cells
- Low aging temperature

Aging is further reduced, particularly for laminated and spray-applied products, with higher-density polymer skins, or by well-adhered facings and coverings with low gas and moisture permeance. An oxygen diffusion rate of less than 0.02 in³/1000 ft²·day for a 0.001 in. thick barrier is one criterion used by some industry organizations for manufacturers of laminated products. The adhesion of any facing must be continuous, and every effort must be made during manufacturing to eliminate or minimize the shear plane layer at the foam/substrate interface (Ostrogorsky and Glicksman 1986). Before 1987, chlorinated fluorocarbons were commonly used as cell gas. Because of their high ozone-depleting potential, chlorofluorocarbons (CFCs) were phased out during the 1990s in accordance with the Montreal Protocol of 1987. Alternatives used today are fluorocarbons, CO_2, N-pentane, and C-pentane.

Closed-cell phenolic-type materials and products, which are blown with similar gases, age differently and much more slowly.

For homogeneous, dense materials, the primary mode of heat transfer is conduction. However, as temperatures increase, heat transfer by radiation (and possibly convection) becomes a greater part of the total. The magnitude of radiation and convection depends on temperature difference, direction of heat flow, nature of the materials involved, and geometry. Because of radiative heat transfer in low-density insulation, measured apparent thermal conductivity depends on test thickness. That thickness effect increases the apparent thermal conductivity measured at installed thickness over that commonly determined at 1 in. (Pelanne 1979). From a thermal resistance standpoint, the effect is small, typically less than 10%, even for thin (e.g., 1 in. thick), low-density (e.g., 0.35 lb/ft^3) insulation. The effect becomes negligible for typical building applications (e.g., 6 in. insulation with a density of 0.7 lb/ft^3).

Environment and application conditions include mean temperature, temperature gradient, moisture content, air infiltration, orientation, and direction of heat flow. The magnitude of effect each has on apparent thermal conductivity varies according to insulation material and form.

The apparent thermal conductivity of insulating materials generally increases with temperature. The rate of change varies with material type and density. Figure 5 shows typical variations with mean temperature. However, some materials, such as fluorocarbon-expanded, closed-cell polyurethanes, have an inflection in the curve where the fluorocarbon changes phase from gas to liquid (see Table 7B in Chapter 25). The apparent thermal conductivity of a sample at one mean temperature (average of the two surface temperatures) only applies to the material at the particular thickness tested. Further testing is required to obtain values suitable for all thicknesses.

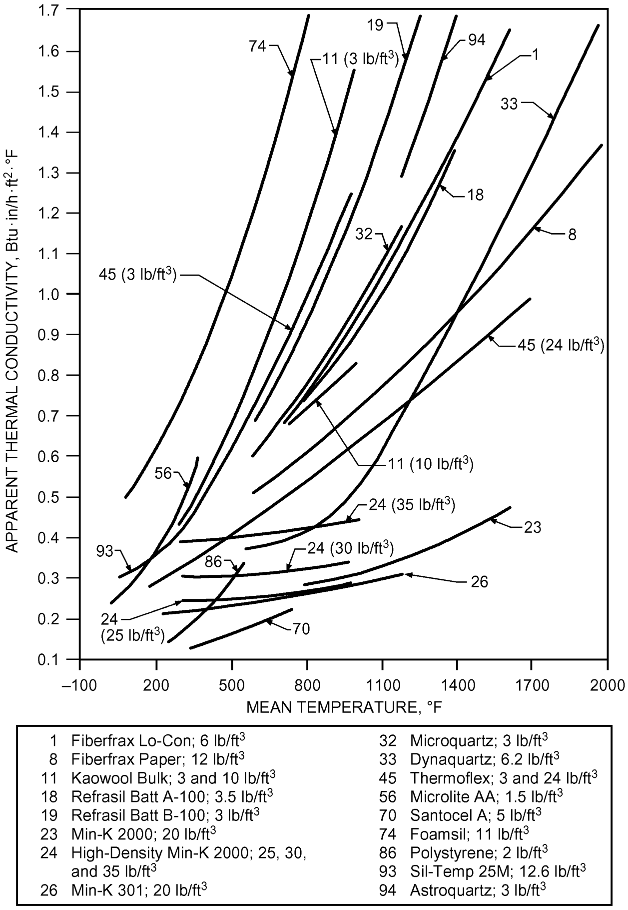

Fig. 5 Apparent Thermal Conductivity Versus Mean Temperature for Various Materials (in Air at Atmospheric Pressure)
(Glaser et al. 1967; Pelanne 1977)

Insulating materials that allow a large percentage of heat transfer by radiation, such as low-density fibrous and cellular products, show the greatest change in apparent thermal conductivity with temperature and surrounding surface emittance.

The effect of temperature on structural integrity is ordinarily not important for most insulation materials in low-temperature applications. In any case, decomposition, excessive linear shrinkage, softening, or other effects limit the maximum temperature for which a material is suited. At extreme temperatures, both high and low, selecting suitable materials is more difficult and must be based on experience and performance data (see Tables 4 and 7B in Chapter 25).

Convection and air infiltration in or through some insulation systems may increase heat transfer across them. Low-density, loose-fill, large open-cell, and fibrous insulation, and poorly designed or installed reflective systems are the most susceptible. The temperature difference across the insulation and the height and width of the insulated space influence the amount of convection. In some cases, natural convection may be inherent to the system (Wilkes and Childs 1992; Wilkes and Rucker 1983), but in many cases it is a consequence of careless design and/or careless construction of the insulated structure (Donnelly et al. 1976). Gaps between board- and batt-type insulations lower their effectiveness. Board-type insulation may not be perfectly square, may be installed improperly, and may be applied to uneven surfaces. A 4% void area around batt insulation can produce a 50% loss in effective thermal resistance for ceiling application with R = 19 h·ft^2·°F/Btu (Verschoor 1977). Similar results have been obtained for wall configurations (Brown et al. 1993; Hedlin 1985; Lecompte 1989; Lewis 1979; Rasmussen et al. 1993; Tye and Desjarlais 1981). As a solution, preformed joints in board-type insulation allow boards to fit together without air gaps. Boards and batts can be installed in two layers, with joints between layers offset and staggered.

The apparent thermal conductivity of insulation materials increases with moisture content. If moisture condenses in the insulation, it not only reduces thermal resistance, but may also physically damage the system. Reduction in thermal resistance depends on material, moisture content, and moisture distribution. Section A3 of the *CIBSE Guide A* (CIBSE 2006) covers thermal properties of building structures affected by moisture.

Apparent thermal conductivity for insulation materials and systems is obtained by standard methods listed in ASTM (2008). The methods apply mainly to laboratory measurements on dried or conditioned samples at specific mean temperatures and temperature gradient conditions. Although fundamental heat transmission characteristics of a material or system can be determined accurately, actual performance in a structure may vary from laboratory results; only field measurements can clarify the differences. Field-test procedures continue to be developed. Envelope design, construction, and material may all affect the procedure to be followed, as detailed in ASTM (1985a, 1985b, 1988, 1990, 1991).

Mechanical Properties

Some insulation is used occasionally to support load-bearing roofs and floors, form self-supporting partitions, or stiffen structural panels. For such applications, the material's strength in compression, tension, shear, impact, flexure, and resistance to vibration may be important. These properties vary with basic composition of the insulation, density, cell size, fiber diameter and orientation, type and amount of binder (if any), and temperature and environmental conditioning.

Health and Safety

Many thermal insulation materials have good resistance to fire, vermin, rot, objectionable odors, and vapors. Some are a potential risk to health and safety, presenting either (1) risk related to storage, handling, and installation or (2) risk that occurs after installation (e.g., aging, fire, or physical disturbance). Potential hazards during manufacture are not considered here. Correct handling, installation, and precautionary measures may reduce or eliminate risks.

Combustion of insulation materials and accessories may release heat, hazardous gases, fibers, and particulates. Manufacturers' recommendations and applicable codes and standards (e.g., ASTM *Standard* C930) give more details.

Acoustics

Some thermal insulation with open, porous surfaces is used as sound absorption material, regardless of whether thermal performance is a design requirement. Thermal insulation with high density and resilient characteristics can act as vibration insulators, either alone or in combination with other materials. Some flexible and semirigid, formed-in-place fibrous materials and rigid fibrous insulation help reduce sound transmission when placed in a composite construction.

Sound-absorbing insulation is normally installed on interior surfaces or used as interior surfacing materials. Rigid sound-absorbing insulation is fabricated into tiles or blocks, edge-treated to facilitate mechanical or adhesive application, and prefinished during manufacture. Insulation units can have a natural porous surface or mechanical perforations to facilitate entry of sound waves; others use a diaphragm or decorative film surfacing attached only to the edges of the units, which allows sound waves to reach the fibrous backing by diaphragm action.

Flexible, semirigid, and formed-in-place fibrous materials used for sound absorption are available in a variety of thickness and densities that determine their sound absorption characteristics.

When density is increased by reducing material thickness, sound absorption is generally reduced; however, as thickness increases, the influence of density decreases.

A wall of staggered-stud construction, finished with airtight gypsum board, that uses resilient clips or channels on one side of the stud reduces sound transmission. Another option is resilient insulation boards of special manufacture to prevent acoustic coupling between surfaces. A sound absorption thermal insulation blanket in a wall cavity also reduces sound transmission, depending on the type of construction.

In floors, resilient channels or separate airtight finished floor and ceiling joists form a discontinuous construction. Sound-absorbing thermal insulation placed in this construction reduces sound transmission. Sound-deadening boards underlying finish flooring absorb impact sounds and reduce airborne and impact sound transmission.

Thermal insulation boards can be placed under mechanical equipment to isolate vibration. The imposed loading and natural resonant frequency of these materials are critical for proper design. Because material must deflect properly under load to provide isolation, the system should be neither over- nor underloaded.

For further information on sound and vibration control, refer to Chapter 47 of the 2007 *ASHRAE Handbook—HVAC Applications*.

Other Properties

Other properties of insulating materials that can be important, depending on application, include density, resilience, resistance to settling, air and vapor permeance, reuse or salvage value, ease of handling, dimensional uniformity and stability, resistance to chemical action and chemical change, resistance to moisture penetration, ease in fabrication, application of finishes, and sizes and thickness obtainable.

Building Materials

The values listed in Table 4 are typically for a mean temperature of 75°F. Thermal conductivity values may vary with temperature: polymers' conductivity generally decreases with temperature, until the glass-transition temperature is reached. This transition occurs at different temperatures for different materials, but is typically at –22 or –40°F; below this threshold, thermal conductivity increases quickly as the temperature decreases.

Table 4 also lists resistance values for materials of specific thickness. Where conductance is required for a material for which only the conductivity is listed, the conductance value can be determined by dividing the conductivity by the desired thickness x, or $C = k/x$. Thermal resistance is the reciprocal of conductance: $R = 1/C$. Resistivity (resistance per unit thickness) is the reciprocal of conductivity, or $1/k$.

Table 4 was revised as a result of ASHRAE research project RP-905 (McGowan 2007). Where possible, sources of data are shown in the Reference column; if no source is specified, the value for that material has been carried over from previous editions of this chapter.

Property Data

Building and Insulating Materials. Steady-state thermal resistances (R-values) of building assemblies (walls, floors, windows, roof systems, etc.) can be calculated from thermal properties of the materials in the component, provided by Table 4, or heat flow through the assembled component can be measured directly with laboratory equipment such as the guarded hot box (ASTM *Standard* C236) or the calibrated hot box (ASTM *Standard* C976). Direct measurement is the most accurate method of determining the overall thermal resistance for a combination of building materials assembled as a building envelope component. However, all combinations may not be conveniently or economically tested in this manner. For many simple constructions, calculated R-values agree reasonably well with values determined by hot box measurement.

Table 4's values were developed by testing under ideal conditions. In practice, overall thermal performance can be reduced significantly by factors such as improper installation, quality of workmanship and shrinkage, settling, or compression of the insulation (Tye 1985, 1986; Tye and Desjarlais 1983). Good workmanship becomes increasingly important as the insulation requirement becomes greater. Therefore, some engineers include additional insulation or other safety factors based on experience in their design.

Because commercially available materials vary, not all values apply to specific products.

Soils

Effective or apparent soil thermal conductivity is difficult to estimate precisely and may change substantially in the same soil at different times because of changed moisture conditions and freezing temperatures. Figure 6 shows the typical apparent soil thermal

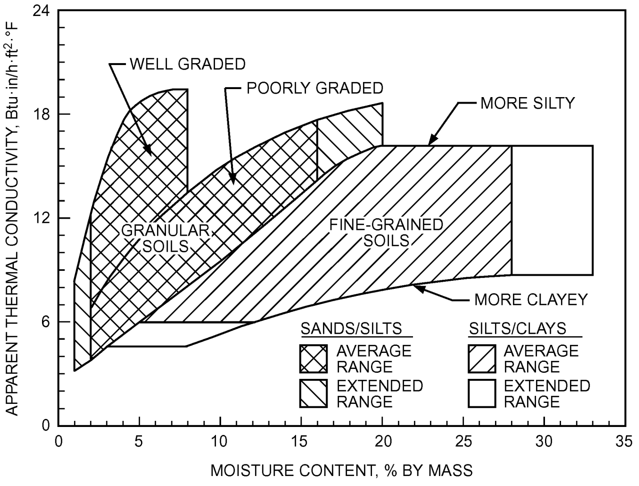

Fig. 6 Trends of Apparent Thermal Conductivity of Moist Soils

Table 5 Typical Apparent Thermal Conductivity Values for Soils, Btu·in/h·ft^2·°F

		Recommended Values for Design[a]	
	Normal Range	Low[b]	High[c]
Sands	4.2 to 17.4	5.4	15.6
Silts	6 to 17.4	11.4	15.6
Clays	6 to 11.4	7.8	10.8
Loams	6 to 17.4	6.6	15.6

[a] Reasonable values for use when no site- or soil-specific data are available.

[b] Moderately conservative values for minimum heat loss through soil (e.g., use in soil heat exchanger or earth-contact cooling calculations). Values are from Salomone and Marlowe (1989).

[c] Moderately conservative values for maximum heat loss through soil (e.g., use in peak winter heat loss calculations). Values are from Salomone and Marlowe (1989).

Table 6 Typical Apparent Thermal Conductivity Values for Rocks, Btu·in/h·ft^2·°F

	Normal Range
Pumice, tuff, obsidian	3.6 to 15.6
Basalt	3.6 to 18.0
Shale	6 to 27.6
Granite	12 to 30
Limestone, dolomite, marble	8.4 to 30
Quartzose sandstone	9.6 to 54

conductivity as a function of moisture content for different general types of soil. The figure is based on data presented in Salomone and Marlowe (1989) using envelopes of thermal behavior coupled with field moisture content ranges for different soil types. In Figure 6, “well-graded” applies to granular soils with good representation of all particle sizes from largest to smallest. “Poorly graded” refers to granular soils with either uniform gradation, in which most particles are about the same size, or skip (or gap) gradation, in which particles of one or more intermediate sizes are not present.

Although thermal conductivity varies greatly over the complete range of possible moisture contents, this range can be narrowed if it is assumed that the moisture contents of most field soils lie between the “wilting point” of the soil (i.e., the moisture content of a soil below which a plant cannot alleviate its wilting symptoms) and the “field capacity” of the soil (i.e., the moisture content of a soil that has been thoroughly wetted and then drained until the drainage rate has become negligibly small). After a prolonged dry spell, moisture is near the wilting point, and after a rainy period, soil has moisture content near its field capacity. Moisture contents at these limits have been studied by many agricultural researchers, and data for different types of soil are given by Kersten (1949) and Salomone and Marlowe (1989). Shaded areas in Figure 6 approximate (1) the full range of moisture contents for different soil types and (2) a range between average values of each limit.

Table 5 summarizes design values for thermal conductivities of the basic soil classes. Table 6 gives ranges of thermal conductivity for some basic classes of rock. The value chosen depends on whether heat transfer is being calculated for minimum heat loss through the soil, as in a ground heat exchange system, or a maximum value, as in peak winter heat loss calculations for a basement. Hence, high and low values are given for each soil class.

As heat flows through soil, moisture tends to move away from the heat source. This moisture migration provides initial mass transport of heat, but it also dries the soil adjacent to the heat source, thus lowering the apparent thermal conductivity in that zone of soil.

Typically, when other factors are held constant,

- *k* increases with moisture content
- *k* increases with increasing dry density of a soil
- *k* decreases with increasing organic content of a soil
- *k* tends to decrease for soils with uniform gradations and rounded soil grains (because grain-to-grain contacts are reduced)
- *k* of a frozen soil may be higher or lower than that of the same unfrozen soil (because the conductivity of ice is higher than that of water but lower than that of typical soil grains). Differences in *k* below moisture contents of 7 to 8% are quite small. At approximately 15% moisture content, *k* may vary up to 30% from unfrozen values.

When calculating annual energy use, choose values that represent typical site conditions as they vary during the year. In climates where ground freezing is significant, accurate heat transfer simulations should include the effect of the latent heat of fusion of water. Energy released during this phase change significantly retards the progress of the frost front in moist soils.

For further information, see Chapter 17, which includes a method for estimating heat loss through foundations.

AIR TRANSMISSION AND HYGRIC PROPERTIES

AIR BARRIERS AND WATER VAPOR RETARDERS

Although the functions of water vapor and air barriers are different, a single component may serve both purposes. The designer should assess needs for vapor and air movement control in the building envelope and provide a system that guarantees the required vapor and air barrier properties.

Air Barriers

An effective air barrier must

- Meet material permeability requirements.
- Be continuous when installed (i.e., tight joints in the air barrier assembly, effective bonds in air barrier materials at intersections such as wall/roof and wall/foundation, tightly sealed penetrations).
- Accommodate dimensional changes caused by temperature or shrinkage without damage to joints or air barrier material.
- Be strong enough to support the stresses applied to the air barrier material or assembly. The air barrier must not be ruptured or excessively deformed by wind or stack effect. Where an adhesive is used to complete a joint, the assembly must be designed to withstand forces that might gradually peel the air barrier material away. Where the air barrier material is not strong enough to withstand anticipated wind and other loads, it must be supported on both sides to account for positive and negative wind gust pressures.

In addition, the following properties may be important, depending on the application:

- Elasticity
- Thermal stability
- Fire and flammability resistance
- Inertness to deteriorating elements
- Ease of fabrication, application, and joint sealing

Control of airflow requires an effective air barrier (also called an **airflow retarder** or **air infiltration barrier**) as well as a vapor retarder. Although flow of dry air may accelerate drying of a wet building component (Karagiozis and Salonvaara 1999a, 1999b), without effective control of airflow, vapor retarders are completely ineffective.

A retarder may control both vapor and airflow (i.e., act as an air/vapor retarder). Many designs are based on this idea, with measures taken to ensure that the vapor retarder is continuous to control airflow. Some designs treat airflow and vapor retarders as separate entities, but an airflow retarder should not be where it can cause moisture to condense if it also has vapor-retarding properties. For example, an air barrier placed on the cold side of a building envelope may cause condensation, particularly if the vapor retarder at the other side is ineffective. Instead, a carefully installed, sealed cold-side air/vapor retarder that has sufficient thermal resistance may lower the potential for condensation by raising the temperature at its indoor surface during the cold season (Ojanen et al. 1994).

Air leakage characteristics can be determined with the ASTM *Standard* E1186 test method for air barriers on the interior side of the building envelope, and described according to ASTM *Standard* E1677. Specific air leakage criteria for air barriers in cold heating climates can be found in Di Lenardo et al. (1995). These specifications call for maximum permissible air leakage rates between 0.01 and 0.04 cfm per square foot (as measured with an air pressure difference of 0.3 in. of water), depending on the water vapor permeance of the outermost layer of the building envelope. The highest leakage rate applies if the permeance of the outermost layer is greater than 10 perms; the lowest rate applies if the permeance is less than 1 perm. Intermediate values are provided. The recommendations apply only to heating climates. (See the section on Air Transmission and Water Vapor Property Data for water vapor permeances of various building materials.)

The required air permeance of an air barrier material has been set by some building codes at 0.004 cfm per square foot at a pressure difference of 0.3 in. of water. An addendum to ASHRAE *Standard* 90.1 in 2008 also referenced this value. ASTM *Standard* E1677 provides an alternative minimum air barrier testing and criteria specifically suitable for framed walls of low-rise buildings.

Air leakage characteristics of an air barrier assembly can be determined with the ASTM *Standard* E2357 test method, which determines the air leakage of three wall specimens: (1) with the air barrier material installed using air barrier accessories alone, (2) with the air barrier material installed and connected to air barrier components (window, doors, and other premanufactured elements) using air barrier accessories, and (3) with an air barrier wall assembly connected to a foundation assembly and roof assembly using air barrier accessories. The test method reports the air leakage rate at a reference pressure difference of 0.3 in. of water.

Specific air leakage criteria for air barrier assemblies can be found in Di Lenardo et al (1995), as well as a 2008 addendum to ASHRAE *Standard* 90.1. These specifications provides classes for air leakage rates of 0.01, 0.02, 0.03, and 0.04 cfm per square foot when measured with an air pressure difference of 0.3 in. of water, depending on the water vapor permeance of the outermost layer of the building envelope. The highest leakage rate applies if the permeance of the outermost layer is greater than 10 perm; the lowest rate applies if the permeance is less than 1 perm. ASTM *Standard* E1677's alternative minimum air barrier testing and criteria are specifically suitable for framed walls of low-rise buildings.

All of the building assemblies are put together and the various air barrier assemblies are connected to form an air barrier system affecting the whole building. A building's air leakage characteristics can be determined with the ASTM *Standard* E779 test method. A 2008 addendum to ASHRAE *Standard* 90.1 referenced a requirement of 0.4 cfm per square foot at 0.3 in. of water pressure difference.

The effectiveness of an air barrier can be greatly reduced if openings, even small ones, exist in it. These openings can be caused by poor design, poor workmanship during application, insufficient coating thickness, improper caulking and flashing, uncompensated thermal expansion, mechanical forces, aging, and other forms of degradation. Faults or leaks typically occur at electrical boxes, plumbing penetrations, telephone and television wiring, and other unsealed openings in the structure. A ceiling air barrier should be continuous at chases for plumbing, ducts, flues, and electrical wiring. In flat roofing, mechanical fasteners are sometimes used to adhere the system to the deck, and often penetrate the air barrier. In heating climates, the resulting holes may allow air exfiltration and accompanying water vapor leakage into the roof. ASTM *Standard* E1186 describes several techniques for locating air leakage sites in building envelopes and air barrier systems.

Because air barrier materials and assemblies resist airflow, they must withstand pressures exerted by chimney (stack) effects, wind effects, or both, during construction and over the building's life. The magnitude of pressure may vary, depending on the type of building and sequence of construction. At one extreme, single-family dwellings may be built with exterior cladding partly or entirely installed and insulation in place before the air barrier is added. Chimney effects in these buildings are small, even in cold weather, so stresses on the air barrier during construction are small. At the other extreme, in tall buildings, wind and chimney-effect forces are much greater. A fragile, unprotected sheet material should not be used as an air barrier or vapor retarder because it will probably be torn by wind before construction is completed.

Note that a small penetration across an air barrier assembly may seriously affect its performance by concentrating air/vapor flow in a small area, resulting in large deposits of water (in some cases turning into ice). As mentioned, calculations of water vapor flow, interstitial condensation, and related moisture accumulation using only water vapor resistances are useless when airflow is involved. More information on air leakage in buildings may be found in Chapter 16.

Vapor Retarders

Water vapor retarders need to be considered in every building design. The need for and type of water vapor retarder used depend on the climate zone, construction type, and building use. Water vapor retarders were designed to protect building elements from water vapor permeating through building materials and then condensing. It is now recognized that it is just as important to allow the building assembly to dry as it is to keep the building assembly from getting wet. In some cases, to allow the building assembly to dry, a water vapor retarder may not be needed or may need to be semipermeable. In other cases, the environmental conditions, building construction, and building use may dictate that a material with very low water vapor permeance should be installed to protect the building components.

The 2007 supplement to the International Codes now lists three water vapor retarder classes:

- **Class I:** 0.1 perm or less
- **Class II:** more than 0.1 perm but less than or equal to 1.0 perm
- **Class III:** more than 1.0 perm but less than or equal to 10 perm

The designer determines the appropriate type of water vapor retarder and its proper location in the building assembly based on climate conditions, other materials used in the building assembly, and the building's use (e.g., intended relative humidity).

Functions and Properties

A vapor retarder slows the rate of water vapor diffusion, but does not totally prevent it. Requirements for vapor retarders in building components are not extremely stringent, because conditions on the inside and outside of buildings vary continually, air movement and ventilation can provide wetting as well as drying at various times, and water vapor entering one side of a building component can be stored and released later.

If conditions are conducive to condensation, water vapor retarders help (1) keep insulation dry; (2) prevent structural damage by rot, corrosion, or expansion of freezing water; and (3) reduce paint problems on exterior wall construction (ASTM *Standard* C755). Vapor retarders control vapor diffusion, so that water vapor enters an assembly more slowly than it leaves. If this can be accomplished through judicious placement of a vapor retarder, the assembly tends to dry out. Another way to look at vapor retarders is that they are the most vapor-resistant layer in the assembly; a capable designer knows where this layer is and ensures that it does not promote condensation or prevent the assembly from drying.

In addition to vapor permeance, the following properties of vapor retarders are important, depending on the application:

- Mechanical strength in tension, shear, impact, and flexure
- Adhesion
- Elasticity
- Thermal stability
- Fire and flammability resistance
- Resistance to other deteriorating elements (e.g., chemicals, UV radiation)
- Ease of fabrication, application, and joint sealing

The vapor retarder's effectiveness depends on its vapor permeance, installation, and location in the insulated section. It is usually located at or near the surface exposed to higher water vapor pressure and higher temperature. For residences with heating systems, this is usually the winter-warm side.

Vapor retarder material is usually a thin sheet or coating. However, a construction of several materials, some perhaps of substantial thickness, can also constitute a vapor retarder system. In fact, designers have many options. For example, airflow and moisture movement might be controlled using an interior finish, such as drywall, to provide strength and stiffness, along with a low-permeability coating, such as vapor-retarding paint, to provide the required low permeance. Other designs may use more than one component. However, (1) any component that qualifies as a vapor retarder usually also impedes airflow, and is thus subject to pressure differences that it must resist; and (2) any component that impedes airflow may also retard vapor movement and promote condensation or frost formation.

Several studies found a significant increase in apparent permeance as a result of small holes in the vapor retarder. For example, Seiffert (1970) reported a 100-fold increase in the vapor permeance of aluminum foil when it is 0.014% perforated, and a 4000-fold increase when 0.22% of the surface is perforated. In general, penetrations particularly degrade a vapor retarder's effectiveness if it has very low permeance (e.g., polyethylene or aluminum foil). In addition, perforations may lead to air leakage, which further erodes effectiveness.

Smart vapor retarders allow substantial summer drying while functioning as effective vapor retarders during the cold season. One type of smart vapor retarder has low permeance to vapor, but is permeable to liquid water, allowing condensed moisture to dry. Korsgaard and Pedersen (1989, 1992) describe such a vapor retarder composed of synthetic fabric sandwiched between staggered strips of plastic film. The fabric wicks free water from the building envelope while the plastic film retards vapor flow into it.

Another type of smart vapor retarder provides low vapor permeance at low relative humidities, but much higher permeance at high relative humidity. During the heating season, indoor humidity usually is below 50% and the smart vapor retarder's permeance is low. In the summer, and on winter days with high solar-heat gains, when the temperature gradient is inward, moisture moving from the exterior of the wall or roof raises the relative humidity at the vapor retarder. This leads to higher vapor permeance and the potential for the wall or roof to dry out. One such vapor retarder is described by Kuenzel (1999). Below 50% rh, the film's permeance is less than 1 perm, but it increases above 60% rh, reaching 36 perm at 90% rh.

Water vapor permeances and permeabilities of some vapor retarders and other building materials are given in Tables 7 and 8. Additional information on control of moisture and airflow using vapor and air barriers may be found in Construction Specifications Canada (1990) and Kumaran (1989).

Classifications

Historically, a material or system with permeance of 1 perm or less qualified as a vapor retarder. Refining this, the Canadian General Standards Board (CGSB) specifies type I vapor retarders as having a permeance of 0.25 perm, and type II as having a permeance of 0.8 perm or less before aging and 1 perm or less after aging.

Water vapor retarders are classified as rigid, flexible, or coating materials. **Rigid retarders** include reinforced plastics, aluminum, and stainless steel. These usually are mechanically fastened in place and are vapor-sealed at the joints. **Flexible retarders** include metal foils, laminated foil and treated papers, coated felts and papers, and plastic films or sheets. They are supplied in roll form or as an integral part of a building material (e.g., insulation). Accessory materials are required for sealing joints. **Coating retarders** may be semifluid or mastic; paint (arbitrarily called surface coatings); or hot melt, including thermofusible sheet materials. Their basic composition may be asphaltic, resinous, or polymeric, with or without pigments and solvents, as required to meet design conditions. They can be applied by spray, brush, trowel, roller, dip or mop, or in sheet form, depending on the type of coating and surface to which it is applied. Potentially, each of these materials is an air barrier; however, to meet air barrier specifications, it must satisfy requirements for strength, continuity, and air permeance.

AIR TRANSMISSION AND WATER VAPOR PROPERTY DATA

Table 7 gives typical water vapor permeance and permeability values for common building materials. These values can be used to calculate water vapor flow through building components and assemblies using equations in Chapter 25.

Water vapor permeability of most building materials is a function of their moisture content, which, in turn, is a function of ambient relative humidity. Permeability values at various relative humidities are presented in Table 8 for several building materials. The same data are presented in Figure 7 for oriented strand board (OSB) and plywood samples. Data in this table and chart are from Kumaran (2002).

Users of the dew-point method may use constant values found in Table 7. However, if condensation in the assembly is predicted, then a more appropriate value should be used. Transient hygrothermal modeling typically uses vapor permeability values that vary with relative humidity, such as those given in Table 8. Table 8 also gives mean air permeability data.

MOISTURE STORAGE DATA

Transient analysis of assemblies requires consideration of the materials' moisture storage capacity. Some materials (called hygroscopic) adsorb or reject moisture to achieve equilibrium with adjacent air. Storage capacity of these materials is typically illustrated by graphs of moisture content versus humidity. The curve showing uptake of moisture (the **sorption isotherm**) is usually above the curve showing drying (the **desorption isotherm**) because the material's uptake of moisture is inhibited by surface tension, as is its release of moisture. Table 9 provides data for these curves for several hygroscopic materials, and Kumaran (1996, 2002) and McGowan (2007) provide actual curves, additional data, and conditions under which they were determined.

Values in Table 9 express moisture content as percentage of dry weight, followed by a subscript value of the relative air humidity at which this moisture content occurs. Note that these values are based on measurement of materials that have reached equilibrium with their surroundings, which in some cases can take many weeks. Most hygrothermal simulation software programs that use these values assume that equilibrium is achieved instantaneously.

Table 7 Typical Water Vapor Permeance and Permeability for Common Building Materials[a]

Material	Weight, lb/100 ft^2	Thickness, in.	Permeance, perm			Permeability, perm-in.
			Dry-Cup	Wet-Cup	Other Method	
Plastic and Metal Foils and Films[b]						
Aluminum foil		0.001	0.0			
		0.00035	0.05			
Polyethylene		0.002	0.16			3.2×10^{-4}
		0.004	0.08			3.2×10^{-4}
		0.006	0.06[b]			3.2×10^{-4}
		0.008	0.04[b]			3.2×10^{-4}
		0.010			3.2	3.2×10^{-4}
Polyvinylchloride, unplasticized		0.002	0.68[b]			
Polyvinylchloride, plasticized		0.004	0.8 to 1.4			
Polyester		0.001	0.73			
		0.0032	0.23			
		0.0076	0.08			
Cellulose acetate		0.01	4.6			
		0.125	0.32			
Liquid-Applied Coating Materials						
Commercial latex paints (dry film thickness)						
Vapor retarder paint		0.0031			0.45	
Primer-sealer		0.0012			6.28	
Vinyl acetate/acrylic primer		0.002			7.42	
Vinyl/acrylic primer		0.0016			8.62	
Semigloss vinyl/acrylic enamel		0.0024			6.61	
Exterior acrylic house and trim		0.0017			5.47	
Paint, 2 coats						
Asphalt paint on plywood					0.4	
Aluminum varnish on wood					0.3 to 0.5	
Enamels on smooth plaster					0.5 to 1.5	
Primers and sealers on interior insulation board					0.9 to 2.1	
Various primers plus 1 coat flat oil paint on plaster					1.6 to 3.0	
Flat paint on interior insulation board					4	
Water emulsion on interior insulation board					30 to 85	
Paint, 3 coats						
Exterior paint, white lead and oil on wood siding			0.3 to 1.0			
Exterior paint, white lead/zinc oxide and oil on wood			0.9			
Styrene/butadiene latex coating	2		11			
Polyvinyl acetate latex coating	4		5.5			
Chlorosulfonated polyethylene mastic	3.5		1.7			
	7.0		0.06			
Asphalt cutback mastic						
1/16 in., dry			0.14			
3/16 in., dry			0.0			
Hot-melt asphalt	2		0.5			
	3.5		0.1			
Building Paper, Felts, Roofing Papers[c]						
Duplex sheet, asphalt laminated, aluminum foil one side	8.6		0.002	0.176		
Saturated and coated roll roofing	65		0.05	0.24		
Kraft paper and asphalt laminated, reinforced	6.8		0.3	1.8		
Blanket thermal insulation back-up paper, asphalt coated	6.2		0.4	0.6 to 4.2		
Asphalt, saturated and coated vapor retarder paper	8.6		0.2 to 0.3	0.6		
Asphalt, saturated, but not coated, sheathing paper	4.4		3.3	20.2		
asphalt felt, 15 lb	14		1.0	5.6		
tar felt, 15 lb	14		4.0	18.2		
Single kraft, double	3.2		31	42		
Polyamide film, 2 mil			1.10	20.53		

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[a] This table allows comparisons of materials, but when selecting vapor retarder materials, exact values for permeance or permeability should be obtained from manufacturer or from laboratory tests. Values shown indicate variations among mean values for materials that are similar but of different density, orientation, lot, or source. Values should not be used as design or specification data. Values from dry- and wet-cup methods were usually obtained from investigations using ASTM *Standards* C355 and E96; other values were obtained by two-temperature, special cell, and air velocity methods.

[b] Usually installed as vapor retarders, although sometimes used as exterior finish and elsewhere near the cold side, where special considerations are then required for warm-side barrier effectiveness.

[c] Low-permeance sheets used as vapor retarders. High permeance used elsewhere in construction.

[d] *Source*: Lotz (1964).

Table 8 Water Vapor Permeability of Building Materials at Various Relative Humidities

Material	Permeability at Various Relative Humidities, perm-in. 10%	30%	50%	70%	90%	Water Absorption Coefficient, lb·h$^{1/2}$/ft^2	Mean Air Permeability, lb/(ft·h·in. Hg)	References/ Comments
Building Board and Siding								
Asbestos cement board, 1/8 in. thickness	←	0.45 to 0.94	→	← N/A	→			Dry cup*
with oil-base finishes	←	0.03 to 0.06	→	← N/A	→			
Cement board, 1/2 in., 71 lb/ft^3	5.1	5.1	6.4	8.2	11.0	0.16	0.24	Kumaran (2002)
Fiber cement board, 1/4 in., 86 lb/ft^3	0.14	0.4	1.1	3.2	10.1	0.31	0.00002	Kumaran (2002)
Gypsum board		14.4		16	21			Kumaran (1996)/NRC
asphalt impregnated	←		0.03		→			
Gypsum wall board, 1/2 in., 39 lb/ft^3	16	19	22	26	31	0.02[c]	0.03	Kumaran (2002)
with one coat primer	5	10	15	20	25	N/A	0.18	Kumaran (2002)
with one coat primer/two coats latex paint	0.75	1.44	2.74	5.48	11.3	N/A	0.02	Kumaran (2002)
Hardboard siding, 3/8 in., 46 lb/ft^3	2.7	2.9	3.2	3.5	3.8	0.0007	0.037	Kumaran (2002)
Oriented strand board (OSB), 41 lb/ft^3, 3/8 in.	0.004	0.1	0.3	0.9	2.6	0.0016	0.008	Kumaran (2002)
7/16 in.	0.02	0.4	0.8	1.6	2.8	0.0022	0.016	Kumaran (2002)
1/2 in.	0.03	0.2	0.6	1.2	1.9	0.0016	0.008	Kumaran (2002)
Particleboard		3.0	4.1	7.0	10.4			Kumaran (1996)
Douglas fir plywood, 1/2 in., 29 lb/ft^3	0.13	0.4	1	2.2	4.5	0.0042[d]	0.0003	Kumaran (2002)
5/8 in., 34 lb/ft^3	0.1	0.3	0.8	2.0	5.5	0.0031	0.008	Kumaran (2002)
Canadian softwood plywood, 3/4 in., 28 lb/ft^3	0.04	0.4	1.6	4.2	9.1	0.0037	0.0002	Kumaran (2002)
Plywood (exterior-grade), 1/2 in., 36 lb/ft^3	0.14	0.25		0.55	5.9			Burch and Desjarlais (1995)
Wood fiber board, 3/8 in., 20 lb/ft^3	8.5	9.3	10	11	12	0.0009	2.0	Kumaran (2002)
1.0 in., 19 lb/ft^3	49	40		59.4	52.9			Burch et al.
Masonry Materials								
Aerated concrete, 28.7 lb/ft^3	8	11	16	23	34	0.44	0.04	Kumaran (2002)
37.5 lb/ft^3	12	15	15	29	43			Kumaran (1996)
Cement mortar, 100 lb/ft^3	9	11	14	17	21	0.25	0.01	Kumaran (2002)
Clay brick, 4 by 4 by 8 in., 124 lb/ft^3	3	3.0	3.3	3.5	3.8	2.1	32	Kumaran (2002)
Concrete, 137 lb/ft^3		0.9	1.0	1.7	4.5			Kumaran (1996)
Concrete block (cored, limestone aggregate), 8 in.	←		19		→			
Lightweight concrete, 69 lb/ft^3		8.4		7.8	12.8			Kumaran (1996)
Limestone, 156 lb/ft^3	0.2	0.2	0.2	0.2	0.2	0.0041	negligible	Kumaran (2002)
Perlite board		19		23	56			Kumaran (1996)
Plaster, on metal lath, 3/4 in.	←		11		→			
on wood lath	←		8		→			
on plain gypsum lath (with studs)	←		15		→			
Polystyrene concrete, 33 lb/ft^3		0.6		0.75	1.9			Kumaran (1996)
Portland stucco mix, 124 lb/ft^3	0.6	0.8	1.1	1.6	2.2	0.15	8.15E-05	Kumaran (2002)
Tile masonry, glazed, 4 in.	←		0.47		→			
Woods								
Eastern white cedar, 3/4 in., 22 lb/ft^3 (transverse)	0.01	0.05	0.3	2.1	14.3	0.02	negligible	Kumaran (2002)
Eastern white pine, 3/4 in., 29 lb/ft^3 (transverse)	0.03	0.1	0.5	1.8	7.0	0.08	8.2E-06	Kumaran (2002)
Pine	0.2	0.4	0.8	2.1	4.3			Kumaran (1996)
Southern yellow pine, 3/4 in., 31.2 lb/ft^3 (transverse)	0.1	0.3	0.9	3.2	11.6	0.02	0.00024	Kumaran (2002)
Spruce (longitudinal)	36	51	58	59	60			Kumaran (1996)
3/4 in., 25 lb/ft^3 (transverse)	0.3	0.7	2.1	6.4	20.2	0.02	0.00041	Kumaran (2002)
Western red cedar, 3/4 in., 21.8 lb/ft^3 (transverse)	0.07	0.2	0.3	0.7	1.6	0.01		Kumaran (2002)
Insulation								
Air (still)	←		120		→			
Cellular glass	←		0.0		→			
Cellulose insulation, dry blown, 2 lb/ft^3	77	96	107	115	122	1.2	2364	Kumaran (2002)
Corkboard		2.05 to 2.6		9.59				
Glass fiber batt, 1 lb/ft^3	118	118	118	118	118	N/A	2038	Kumaran (2002)
Glass-fiber insulation board, 15/16 in., 7.5 lb/ft^3		163			104			Burch et al.

Table 8 Water Vapor Permeability of Building Materials at Various Relative Humidities (*Continued*)

Material	Permeability at Various Relative Humidities, perm-in.					Water Absorption Coefficient, lb·h$^{1/2}$/ft^2	Mean Air Permeability, lb/(ft·h·in. Hg)	References/ Comments
	10%	30%	50%	70%	90%			
facer, 1/16 in., 55 lb/ft^3	0	0		0.01	0.03			Burch et al.
Mineral fiber insulation, 2 to 12 lb/ft^3		48		60	171			Kumaran (1996)
Mineral wool (unprotected)	←		168		→			
Phenolic foam (covering removed)	←		26		→			
Polystyrene								
expanded, 1 lb/ft^3	2.0	2.3	2.7	3.2	3.8	N/A	0.09	Kumaran (2002)
extruded, 2 lb/ft^3	0.8	0.8	0.8	0.8	0.8	N/A		Kumaran (2002)
Polyurethane								
expanded board stock (R = 11 h·ft^2·°F/Btu)		0.4 to 1.58						
sprayed foam, 2.4 lb/ft^3	1.6	1.7	1.9	2.0	2.2	N/A	0.000082	Kumaran (2002)
0.4 to 1/2 lb/ft^3	88	88	88	88	88	N/A	0.034	Kumaran (2002)
Polyisocyanurate insulation, 1.7 lb/ft^3	2.8	3.1	3.5	4.0	4.5	N/A		Kumaran (2002)
Polyisocyanurate glass-mat facer, 0.01 in., 26.8 lb/ft^3	0.3	0.6		0.9	1.6			Burch et al.
Structural insulating board, sheathing quality	←		20 to 50		→			
interior, uncoated, 5/16 in.	←		26.1 to 47		→			
Unicellular synthetic flexible rubber foam		0.02						
Foil, Felt, Paper								
Bituminous paper (#15 felt), 2 mil, 54 lb/ft^2 (transverse)	0.2	0.2	0.2	0.27	0.8	0.006	20	Kumaran (2002)
Asphalt-impregnated paper								
10 min rating, 5 mil, 5.9 lb/ft^2 (transverse)	0.16	0.29	0.53	1.01	2.1	0.012	9	Kumaran (2002)
30 min rating, 6 mil, 8.2 lb/ft^2 (transverse)	0.3	0.51	0.88	1.58	3.2	0.011	54	Kumaran (2002)
60 min rating, 9 mil, 16.1 lb/ft^2 (transverse)	1.03	1.31	1.67	2.18	2.9	0.014	58	Kumaran (2002)
Spun bonded polyolefin (SBPO)								
4 mil, 0.87/ft^2 (transverse)	2.99	2.99	2.99	2.99	2.99	0.0038	4	Kumaran (2002)
with crinkled surface, 3 to 4 mil, 0.92 lb/ft^2 (transverse)	2.17	2.17	2.17	2.17	2.17	0.0029	2	Kumaran (2002)
Wallpaper								
paper		0.08		0.8 to 1.2				Kumaran (1996)
textile		0.03		0.5 to 1.6				Kumaran (1996)
vinyl, 5 mil, 5.9 lb/ft^2 (transverse)	0.05	0.1	0.14	0.22	0.32	0.003	0.041	Kumaran (2002)
Other Construction Materials								
Built-up roofing (hot-mopped)	←		0.0		→			
Exterior insulated finish system (EIFS), 0.17 in. acrylic, 71 lb/ft^3	0.06	0.06	0.06	0.06	0.06	0.0065	0	Kumaran (2002)
Glass fiber reinforced sheet,								
acrylic, 1/16 in.	←		0.01		→			
polyester, 1/16 in.	←		0.02		→			

*Historical data, no reference available

N/A = Not available

Maximum values in Table 9 are those that could be realistically measured in laboratory conditions, so not all materials have a listing for a maximum moisture content at 100% rh. For those that do, there are sometimes two listings: the moisture content measured when the material's capillary pores were saturated (shown as 100c) and the value at total saturation (shown as 100t). It is understood that the moisture content of any material would be 0.0 at a theoretical relative humidity of 0%, so this point is not shown in the table.

Figure 8 shows example of as a conventional sorption isotherm graph. Curves show sorption (wetting) and desorption (drying), for data in Table 9 and from Kumaran (2002). As Figure 8 illustrates, data in Table 9 were selected to provide an accurate representation of the sorption isotherm, although not all data from the original source are represented.

CODES AND STANDARDS

ASHRAE. 2007. Energy standard for buildings except low-rise residential buildings. ANSI/ASHRAE/IESNA *Standard* 90.1-2007.

ASTM. 2005. Standard terminology relating to thermal insulation. *Standard* C168-05a. American Society for Testing and Materials, West Conshohocken, PA.

ASTM. 2004. Standard test method for steady-state heat flux measurements and thermal transmission properties by means of the guarded-hot-plate apparatus. *Standard* C177-04. American Society for Testing and Materials, West Conshohocken, PA.

ASTM. 2005. Standard test method for steady-state heat transfer properties of horizontal pipe insulation. *Standard* C335-05ae1. American Society for Testing and Materials, West Conshohocken, PA.

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ASTM. 2003. Standard practice for selection of vapor retarders for thermal insulation. *Standard* C755-03. American Society for Testing and Materials, West Conshohocken, PA.

ASTM. 2005. Standard classification of potential health and safety concerns associated with thermal insulation materials and accessories. *Standard* C930-05. American Society for Testing and Materials, West Conshohocken, PA.

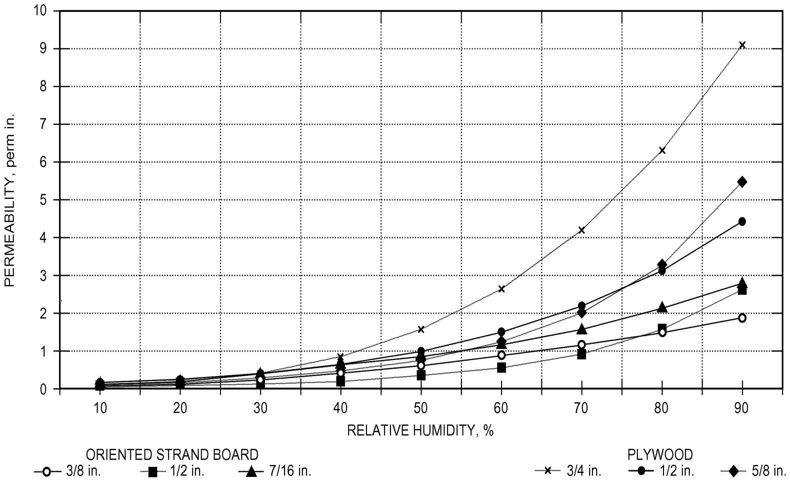

Fig. 7 Permeability of Wood-Based Sheathing Materials at Various Relative Humidities

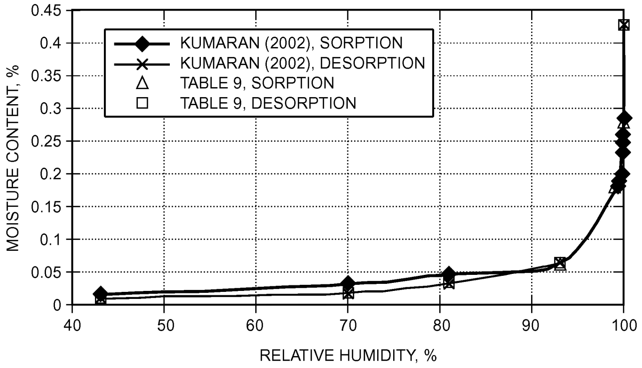

Fig. 8 Sorption/Desorption Isotherms, Cement Board

ASTM. 2007. Standard practice for calculating thermal transmission properties from steady-state measurements. *Standard* C1045-07. American Society for Testing and Materials, West Conshohocken, PA.

ASTM. 2005. Standard test method for thermal performance of building materials and envelope assemblies by means of a guarded hot box apparatus. *Standard* C1363-05. American Society for Testing and Materials, West Conshohocken, PA.

ASTM. 2005. Standard test methods for water vapor transmission of materials. *Standard* E96/E96M-05. American Society for Testing and Materials, West Conshohocken, PA.

ASTM. 2003. Standard practices for air leakage site detection in building envelopes and air barrier systems. *Standard* E1186-03. American Society for Testing and Materials, West Conshohocken, PA.

ASTM. 2005. Standard specification for an air retarder (AR) material or system for low-rise framed building walls. *Standard* E1677-05. American Society for Testing and Materials, West Conshohocken, PA.

ASTM. 2005. Standard test method for determining air leakage of air barrier assemblies. *Standard* E2357-05. American Society for Testing and Materials, West Conshohocken, PA.

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Table 9 Sorption/Desorption Isotherms of Building Materials at Various Relative Humidities

Material	Sorption, % Moisture Content at % Relative Humidity						Desorption, % Moisture Content at % Relative Humidity						References
Building Board and Siding													
Cement board, 1/2 in., 70 lb/ft^3	1_{43}	1.9_{70}	3.4_{81}	6.1_{93}	42.7_{100t}		1.6_{43}	3.2_{70}	4.6_{81}	6.2_{93}	$18_{99.27}$	$28_{99.93}$	Kumaran (2002)
Fiber cement board, 5/16 in., 86 lb/ft^3	$4_{50.6}$	$5.8_{70.4}$	$16.8_{89.9}$	34.7_{100t}			$6.6_{50.5}$	$12.3_{70.5}$	$19.6_{90.6}$	$31.3_{95.32}$	$32.5_{99.49}$	$33.9_{99.93}$	Kumaran (2002)
Gypsum wall board, 1/2 in., 39 lb/ft^3	$0.4_{50.5}$	$0.65_{70.5}$	$1.8_{90.8}$	4.2_{94}	68.9_{100c}	113_{100t}	$0.99_{50.4}$	$1.32_{71.5}$	$1.69_{84.8}$	$1.82_{88.3}$			Kumaran (2002)
Hardboard siding, 7/16 in., 46 lb/ft^3	$4.7_{50.3}$	$6.9_{69.6}$	$13.1_{91.3}$	90_{100t}			$4.4_{50.3}$	$7.6_{69.2}$	$13.4_{91.3}$	$38_{91.3}$			Kumaran (2002)
Oriented strand board (OSB), 3/8 in., 41 lb/ft^3	$4.6_{48.9}$	$7.6_{69.1}$	$14.7_{88.6}$	126_{100c}			$6.9_{49.9}$	$9.1_{69.4}$	$16.2_{90.3}$	$17.3_{92.3}$	$39.3_{99.3}$	$60.6_{99.8}$	Kumaran (2002)
7/16 in., 41 lb/ft^3	$5.4_{48.9}$	$8.2_{69.1}$	$14.7_{88.6}$	160_{100t}			$7.9_{49.9}$	$9.9_{69.4}$	$17.4_{90.3}$	$39.1_{99.3}$	$62.7_{99.8}$		Kumaran (2002)
1/2 in., 41 lb/ft^3	$4.6_{48.9}$	$7.8_{69.1}$	$14.8_{88.6}$	124_{100t}			$7.9_{49.9}$	$10_{69.4}$	$17.6_{90.3}$	$20_{92.3}$	$42_{99.3}$	59.5	Kumaran (2002)
Particle board, 3/4 in., 47 lb/ft^3	$1.2_{11.3}$	$6.3_{57.6}$	$9.7_{78.6}$	$11.3_{84.1}$	$15.9_{93.6}$	$21.5_{97.3}$	$1.7_{11.3}$	$8.8_{57.6}$	$14_{78.6}$	$16.6_{84.1}$	$19_{93.6}$	$23.3_{97.6}$	Kumaran (1996)
Plywood, 1/2 in.	$7_{48.9}$	$9.2_{69.1}$	$15.8_{88.6}$	170_{100t}			$8.4_{49.9}$	$10.8_{69.4}$	$18.2_{90.3}$	$19_{92.3}$	$70_{99.3}$	101	Kumaran (2002)
5/8 in.	$6.8_{48.9}$	$9.6_{69.1}$	$16.8_{88.6}$	140_{100t}			$8.6_{49.9}$	$11.3_{69.4}$	$19.8_{90.3}$	$19.3_{92.3}$	$47_{99.3}$	79	Kumaran (2002)
3/4 in.	$6.7_{48.9}$	$10.1_{69.1}$	$17.6_{88.6}$	190_{100t}			$8.9_{49.9}$	$11.3_{69.4}$	$19.3_{90.3}$	$20.7_{92.3}$	$66_{99.3}$	$99_{99.8}$	Kumaran (2002)
Plywood (exterior-grade), 1/2 in., 36 lb/ft^3	$1.83_{11.3}$	6.9_{58}	$9.5_{78.7}$	$12.1_{84.5}$	$17.9_{93.8}$	22.1	$2.09_{11.3}$	9.3_{58}	$13.7_{78.7}$	$15.2_{84.5}$	$19.8_{93.8}$	23.4	Burch et al.
Wood fiber board, 7/16 in., 20 lb/ft^3	$4.6_{50.6}$	$7.4_{70.5}$	$15.8_{91.1}$	304			$3.9_{50.6}$	$7.4_{71.1}$	$15_{90.6}$	$230_{99.71}$	$230_{99.85}$	$230_{99.93}$	Kumaran (2002)
1.0 in., 18.7 lb/ft^3	$0.63_{11.3}$	5.7_{58}	$9.2_{78.7}$	$11.3_{84.5}$	$16.4_{93.8}$	$24.6_{97.4}$	$1.26_{11.3}$	7.6_{58}	$12_{78.7}$	$14.6_{84.5}$	$20.6_{93.8}$	$28.1_{97.4}$	
Masonry Materials													
Aerated concrete, 29 lb/ft^3	$1.1_{50.6}$	$2.1_{71.5}$	$5_{88.1}$	83_{100c}	172		$1.1_{50.6}$	$2.2_{71.5}$	$6.3_{88.1}$	$34_{97.81}$	$72_{99.85}$	$92_{99.99}$	Kumaran (2002)
37.5 lb/ft^3	$1.8_{17.8}$	$3.2_{75.8}$	$4.6_{90.3}$	$6.4_{92.4}$	$9.6_{95.9}$	$17.5_{98.4}$	$2.3_{17.8}$	2.8_{33}	$4_{55.2}$	$6.6_{75.6}$	$15.4_{91.6}$	36.5_{98}	Kumaran (1996)
Cement mortar, 100 lb/ft^3	$0.42_{49.9}$	$2.3_{70.1}$	$5.3_{89.9}$	26_{100t}			$3.4_{49.9}$	$4.4_{70.2}$	$6.1_{89.9}$	$17_{98.9}$	$22_{99.63}$	$25_{99.93}$	Kumaran (2002)
Clay brick, 4 × 4 × 8 in., 124 lb/ft^3	0.08_{50}	$0.12_{69.1}$	$0.1_{91.2}$	9.9_{100t}			0_{50}	$0_{91.2}$	$4.5_{98.9}$	$6_{99.63}$	$8.2_{99.71}$	$9.1_{99.93}$	Kumaran (2002)
Concrete, 138 lb/ft^3	$0.88_{25.2}$	$1.15_{44.9}$	1.74_{65}	2.62_{80}	$3.35_{89.8}$	$4.45_{98.2}$	0.94_{20}	$2.19_{45.4}$	$2.98_{65.6}$	$3.85_{84.8}$	$4.57_{94.8}$		Kumaran (1996)
Lightweight concrete, 98 lb/ft^3	$2.9_{24.4}$	$3.4_{45.2}$	$4_{65.2}$	4.6_{85}	6.6_{98}		$3.1_{19.6}$	4.4_{40}	$5.2_{59.8}$	$6_{79.6}$	$7.1_{94.7}$		Kumaran (1996)
Limestone, 156 lb/ft^3	0_{50}	0_{70}	$0.1_{88.5}$	1.8_{100t}			$0_{70.5}$	$0.1_{88.6}$	$0.21_{95.3}$	$0.5_{98.9}$	$0.6_{99.27}$	$1.3_{99.93}$	Kumaran (2002)
Perlite board	130_{33}	160_{52}	260_{75}	380_{86}	800_{97}	$1170_{99.8}$							Kumaran (1996)
Portland stucco mix, 124 lb/ft^3	3_{50}	$3.7_{70.3}$	$5.8_{89.9}$	12_{100t}			4.2_{50}	$5.2_{70.3}$	$7_{90.3}$	$10.3_{95.29}$	$11.6_{98.9}$	$11.7_{99.93}$	Kumaran (2002)
Woods													
Eastern white cedar, 1 in., 22.5 lb/ft^3	$3.4_{49.8}$	7.6_{70}	$12.8_{88.5}$	228_{100t}			1.7_{50}	$7.4_{70.5}$	$11.9_{88.7}$	$85_{98.9}$	$118_{99.63}$	$176_{99.92}$	
Eastern white pine, 1 in., 28.7 lb/ft^3	$3.2_{49.8}$	7.6_{70}	$12_{88.5}$	192_{100t}			3.2_{50}	$9_{70.5}$	$12.4_{88.7}$	$84_{99.78}$			
Southern yellow pine, 1 in. 31 lb/ft^3	$3.6_{49.8}$	8.1_{70}	$15.2_{88.5}$	158_{100t}			4.3_{50}	$10_{70.5}$	$15.6_{88.7}$	$57_{99.78}$			
Spruce (transverse), 25 lb/ft^3	$4.1_{49.8}$	9.2_{70}	$16.7_{88.5}$	228_{100t}			4.9_{50}	$11.3_{70.5}$	$17.7_{88.7}$	$148_{95.96}$	$187_{99.78}$		
Western red cedar, 1 in., 21.8 lb/ft^3	$3.4_{49.8}$	6_{70}	$9.6_{88.5}$	228_{100t}			1_{50}	$9_{70.5}$	$13.3_{88.7}$	$113_{99.78}$			
Insulation													
Cellulose, dry-blown, 1.87 lb/ft^3	$6.1_{50.5}$	$9.6_{71.5}$	$24_{88.1}$				$5_{50.2}$	$12_{72.8}$	26_{88}				Kumaran (2002)
Glass fiber batt, 0.72 lb/ft^3	$0.21_{50.6}$	$0.34_{71.5}$	$0.75_{88.1}$				$0.24_{50.4}$	$0.35_{71.4}$	$0.67_{88.2}$				Kumaran (2002)
Glass-fiber board, 0.9 in., 7.5 lb/ft^3	$0.16_{11.3}$	0.75	$0.82_{78.7}$	$0.96_{84.5}$	$1.3_{93.8}$	$2.03_{97.4}$	$0.43_{11.3}$	$0.86_{32.8}$	1.11_{58}	$1.26_{84.5}$	$1.74_{93.8}$	$2.16_{97.4}$	Burch et al.
Glass-fiber board facer, 0.06 in., 55 lb/ft^3	$0.09_{11.3}$	0.53_{58}	$0.76_{78.7}$	$0.84_{84.5}$	$1.14_{93.8}$	$1.54_{97.4}$	$0.18_{11.3}$	0.56_{58}	$0.87_{78.7}$	$1.09_{84.5}$	$1.45_{93.8}$	$1.81_{97.4}$	Burch et al.
Mineral fiber, 2.5 lb/ft^3	$0.5_{20.1}$	$0.55_{45.4}$	0.59_{65}	$0.7_{85.2}$	$0.76_{94.5}$	$0.8_{97.5}$	$0.5_{20.1}$	$0.58_{44.9}$	$0.63_{64.9}$	$0.81_{84.5}$	$1.1_{94.7}$	$1.6_{97.8}$	Kumaran (1996)
Polystyrene, expanded, 0.92 lb/ft^3	$0.4_{50.4}$	$0.3_{68.3}$	$0.2_{88.3}$				$0.4_{50.1}$	$0.5_{67.9}$	$0.5_{87.9}$				Kumaran (2002)
extruded, 1.79 lb/ft^3	$0.6_{50.4}$	$0.5_{68.3}$	$0.4_{88.3}$				$0.5_{50.1}$	$0.5_{67.9}$	$0.4_{87.9}$				Kumaran (2002)
Polyurethane, sprayed foam, 2.43 lb/ft^3	$1.3_{50.4}$	$1.7_{68.3}$	$2_{88.4}$				$1.1_{50.1}$	$1.5_{67.9}$	$1.8_{87.9}$				Kumaran (2002)
0.4 to 1/2 lb/ft^3	$0.5_{50.4}$	$1_{70.2}$	$1.6_{90.3}$				$1_{50.5}$	$2.1_{70.9}$	$7_{91.3}$				Kumaran (2002)
Polyisocyanurate, 1.65 lb/ft^3	$1.3_{50.4}$	$1.7_{68.3}$	$2.1_{88.3}$				$1.1_{50.1}$	$1.5_{67.9}$	$1.9_{87.9}$				Kumaran (2002)
Polyisocyanurate glass facer, 0.04 in., 26.8 lb/ft^3	$1.36_{11.3}$	4.5_{58}	$6.8_{78.7}$	$9_{84.5}$	$12.5_{93.8}$	$17.9_{97.4}$	$0.89_{11.3}$	5.8_{58}	$8.3_{78.7}$	10.9	$14.4_{93.8}$	$18.4_{97.4}$	Burch et al.

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