Water Vapor Permeability and Thermal Conductivity as a Function of Temperature and Relative Humidity

Ilkka Valovirta

Juha Vinha
Member ASHRAE

ABSTRACT

This paper deals with water vapor transmission properties and thermal conductivity at various temperatures and relative humidities, especially in Nordic climatic conditions. The paper presents measured data for mineral wool, cellulose, flax and sawdust insulation materials, gypsum boards, fiberboards, wood hardboard, oriented strandboard, plywood, wood, weatherization membranes, bitumen paper, and felt and building papers. Effects of increase of vapor permeability as a function of relative humidity, decrease of vapor permeability as a function of temperature, and increase of thermal conductivity as a function of temperature and relative humidity are discussed. In a Nordic climate, a sufficient water vapor resistance of the interior section of building shell and sufficient thermal insulation are required. On the other hand, sheathing must be permeable to water vapor. Changes in material property values can have a considerable effect on the performance of the shell structure.

INTRODUCTION

The physical properties of building materials should always be measured at the same conditions that prevail in real-life conditions. This is extremely important when considering the modeling of building physical behavior with modern simulation tools. Advantages of these tools cannot be fully exploited if correct material data are not available. In addition, knowledge about the properties of materials helps to understand the behavior of a building shell containing several material layers. In Finland, there are long periods during winter months when the temperature is between –30°C and –10°C (–22°F and 14°F). Temperature extremes in northern Finland are ca. –50°C (–58°F). During winter, relative humidity is usually between 90% and 100%. Material values measured at standard laboratory conditions are not necessarily valid in these conditions.

Material data were measured for several materials in various conditions (Tveit 1966; Burch et al. 1992; Galbraith 1993; Galbraith and Mclean 1993; Kumaran 1996, 2002.) New data are still needed because new products appear on the market, and manufacturers also make changes to their existing products.

This paper deals with water vapor transmission and thermal conductivity of building materials used in wall assemblies of wood-framed houses. Material properties have been measured in various relative humidities and temperatures. The temperature range used in tests was from –10°C to +23°C (from 14°F to 73°F), which enabled measurements below the freezing point of water. The relative humidity range was from 33% to 97%. Perhaps the most interesting combination of these conditions was low temperature and high relative humidity because conditions like this are dominating in outer parts of the building envelope, e.g., sheathing, in wintertime. The lowest temperature was chosen to be –10°C (14°F) because one purpose of the material tests was to supplement laboratory tests done for exterior wall assemblies at temperatures between –10°C and +20°C (14°F and 68°F) (Vinha and Käkelä 1999; Vinha et al. 2001.)

For some materials, vapor permeability rises when RH rises. On the other hand, vapor permeability decreases when the temperature drops below 0°C. Therefore, the functionality of a shell structure should be studied during various seasons using relevant material properties.

Ilkka Valovirta is a research scientist and **Juha Vinha** is a senior research scientist in the Department of Civil Engineering, Tampere University of Technology, Tampere, Finland.

Dependence between thermal conductivity and temperature is well known as the effect of moisture to heat transfer of materials. However, there is need to measure data on a wide range of temperature and humidity conditions. In Europe, thermal conductivities are traditionally measured at +10°C (50°F) mean temperature, which is far from the extremes of a Nordic climate.

MATERIALS TO BE TESTED

Materials to be tested were common materials used in external wall assemblies in Finland. With the exception of three materials (sawdust and chipping, which represented traditional insulation materials, and wood), all of the materials are industrially manufactured. The material selection included all of the layers of a typical wood-framed exterior wall. The materials and some of their characteristics are listed in Table 1.

All materials except B4, I6, and I7 are industrially produced. Thickness of loose-fill insulation products was chosen to be 50 mm (2 in.) because all blanket-form insulation products were available in this thickness. Thickness of wood was chosen to be 10 mm to achieve reasonable testing time in water vapor transmission tests because water vapor transmission perpendicular to grain is rather slow.

Thermal conductivity was not measured for papers, foils, or similar thin products (materials F1-F15). Thermal conductivity of these products is not a key factor in building shell design. Also, their water vapor transmission properties were expressed as vapor permeances because determining vapor permeability with the test method used in this study was quite indifferent. This is due to the small thickness of materials. Water vapor transmission properties were not measured at temperatures below +23°C for materials that are only used in the interior side of building shell.

There were three identical specimens of every material in each test.

TEST METHODS AND TEST CONDITIONS

Water Vapor Transmission Tests

Water vapor transmission properties were measured using the wet cup method. The method is based on the diffusion of water vapor from an area with higher partial pressure of water vapor to an area with lower partial pressure. The difference between partial pressures causes diffusion. When performing a wet cup test, the test specimen is installed as a cover to the cup. There is saturated salt solution inside the cup, which creates certain relative humidity (RH) inside of the cup. The test assembly is set in a climate chamber with lower RH, which prevails inside the cup. When temperatures of the cup and its environment are the same, partial vapor pressure is greater inside the cup than outside. This causes moisture flow across the test specimen. Moisture flow is measured by weighing the cup periodically. The principle of this method is shown in Figure 1.

The wet cup method is widely used and standardized (ASTM 1990; CEN 2001; DIN 1987; SIS 1980). The method used in this test series is a combination of these standards and other instructions (Hedenblad 1996).

Tests were performed at temperatures of +23, +5, and –10°C (73°F, 41°F, and 14°F). The RH inside the climate chamber was 33%. RH conditions inside the cups were 55%, 75%, 86%, and 97%, except in a –10°C (14°F) temperature, where 45%, 76%, and 86% were used. Other salt solutions did not perform well below the freezing point of water. The test procedure is described in detail by Mikkilä (2001.) The cups were of plastic and had a diameter of 110 mm (4.33 in.).

Mathematical treatment of measured values differs from the traditional method, where moisture transport properties are declared at average relative humidity of the test specimen. In this study, measurements were done using several relative humidities inside the cup and having constant RH in the climate chamber. A mathematical equation of the moisture flow rate (g) as a function of difference in humidity by volume inside and outside of the cup ($\Delta\nu$) was determined from the results. This was done using regression analysis. The method is described in detail by Bazant and Najjar (1972), Hedenblad (1996), Lackey et al. (1997), and Kumaran (1998).

According to Fick's first law, one-dimensional moisture transport in a stationary state can be expressed as follows:

$$g = \delta_\nu \frac{\partial \nu}{\partial x} \tag{1}$$

where

g = mass flow through the specimen (kg/m^{2}s or gr/ft^2 h)

δ_ν = vapor permeability with regard to humidity by volume (m^2/s or ft^2/h)

ν = water vapor content of air (kg/m^3 or gr/cb ft)

x = coordinate parallel to mass flow (m or ft)

Equation 1 can be written as follows:

$$\int g \cdot \partial x = -\int \delta_\nu \cdot \partial \nu \tag{2}$$

where both sides are integrated. The left side is integrated from $x = 0$ to $x = L$, where L is thickness of the specimen. The right side is integrated from ν_1 to ν_2, where ν_1 is the water vapor content outside the cup (constant) and ν_2 is the water vapor content inside the cup. The result is

$$g \cdot L = \int_{\nu_1}^{\nu_2} \delta_\nu(\nu) \cdot \partial \nu \ . \tag{3}$$

When Equation 3 is differentiated with ν_2, the following equation can be written:

$$\frac{\partial g}{\partial \nu_2} \cdot L = \frac{\partial}{\partial \nu_2} \int_{\nu_1 = const.}^{\nu_2} \delta_\nu(\nu) \cdot \partial \nu = \delta_\nu(\nu_2) \tag{4}$$

Equation 4 can be written as follows (Mikkilä 2001):

Table 1. Materials Used in Laboratory Measurements

Material ID	Material Type	Nominal Thickness (mm)	Nominal Thickness (in.)	Mean Density (kg/m^3)	Mean Density (lb/ft^3)	Used As
W1	Gypsum board	9	0.35	774	48.3	Sheathing
W2	Porous fiberboard, wood	25	1	280	17.5	Sheathing
W3	Glass wool board	30	1.2	73	4.6	Sheathing
W4	Glass wool board	25	1	104	6.5	Sheathing
W5	Rock wool board	30	1.2	92	5.8	Sheathing
W6	Rock wool board	30	1.2	120	7.5	Sheathing
W7	Cellulose board	25	1	63	3.9	Sheathing
W8	Hardboard, wood	4	0.16	1140	71.2	Sheathing
W9	Moisture-proof chipboard	12	0.47	723	45.2	Sheathing
W10	Fir plywood, 3 ply	9	0.35	394	24.6	Sheathing/ interior board
W12	Porous fiberboard, wood	12	0.47	270	16.9	Sheathing
F1	Weatherization membrane	0.1	0.004	362	22.6	Sheathing
F2	Weatherization membrane	0.1	0.004	247	15.4	Sheathing
F3	Weatherization membrane	0.1	0.004	232	14.5	Sheathing
F4	Weatherization membrane	0.1	0.004	393	24.6	Sheathing
F5	Bitumen paper	0.1	0.004	938	58.6	Sheathing
F6	Bitumen paper	0.1	0.004	537	33.5	Sheathing
F7	Bitumen felt	0.2	0.008	863	53.9	Sheathing
F8	Bitumen paper	0.1	0.004	841	52.5	Sheathing
F9	Bitumen paper	0.1	0.004	618	38.6	Sheathing
F10	Plastic coated paper	0.1	0.004	941	58.8	Vapor/ air barrier
F11	Wax-treated paper	0.1	0.004	882	55.1	Vapor retarder/ air barrier
F12	Plastic-coated paper	0.1	0.004	756	47.2	Vapor retarder/ air barrier
F13	Bitumen paper	0.1	0.004	800	50.0	Vapor retarder/ air barrier
F14	Polyethylene sheet	0.2	0.008	920	57.5	Vapor/ air barrier
F15	Building paper	0.1	0.004	800	50.0	Vapor retarder/ air barrier
B1	Gypsum board	13	0.51	574	35.9	Interior board
B2	Chipboard	12	0.47	592	37.0	Interior board
B3	Oriented strand board	12	0.47	646	40.4	Interior board
B4	Wood, pine	10	0.4	532	33.2	Various (studs, panels, etc.)
I1	Glass wool batt	50	2.0	22	1.4	Thermal insulation
I2	Rock wool batt	50	2.0	37	2.3	Thermal insulation
I3	Cellulose batt	50	2.0	51	3.2	Thermal insulation
I4	Cellulose, loose-fill	50	2.0	37	2.3	Thermal insulation
I5	Flax batt	50	2.0	39	2.4	Thermal insulation
I6	Sawdust	50	2.0	168	10.5	Thermal insulation
I7	Chipping	50	2.0	130	8.1	Thermal insulation

$$\frac{\partial g}{\partial \nu_2} = \frac{\delta_\nu}{L} = W_\nu \qquad (5)$$

where

W_ν = vapor permeance with regard to water vapor content (m/s or ft/h)

Water vapor transmission properties are often expressed with regard to partial pressure of water vapor. This can be done using Equation 6.

$$\delta_p = W_p \cdot L = \frac{M_w}{R \cdot T} \cdot \delta_\nu \qquad (6)$$

where

M_w = molecular weight of water vapor (0.01802 kg/mol or 0.03974 lb/mol)

R = universal gas constant (8.314 J/mol·K or 1.986 Btu/lb·mol·°R)

T = absolute temperature (K or °R)

When considering the practical application of measured data, it would be useful to show water vapor transmission values as a function of relative humidity, not ν_2 or partial pressure of water vapor. This is easy because relative humidity is defined as a quotient of water vapor content and saturation water vapor content. Because the temperature was held constant during the test, saturation water vapor content was constant, and curves of g and δ_ν could be drawn using relative humidity in the x-axis instead of ν_2 (see Figure 2). A difference between mathematical processes of calculating water vapor transmission properties can also be seen there. In this paper, water vapor transmission properties have been shown with regard to partial pressure as a function of relative humidity.

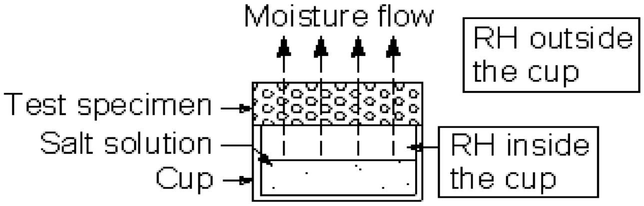

Figure 1 *Principle of wet cup method.*

In brief, water vapor permeability can be obtained by determining the equation of moisture flow rate and differentiating it. Units that describe the vapor transmission can be conducted after that procedure.

In practice, the equation between water vapor content and moisture flow is chosen by trying different types of equations and choosing the one that gives the best correlation with measurements. In this study, the equation of moisture flow rate was either linear (first degree), polynomial (second degree), or exponential, depending on which model gave the biggest correlation factor. Therefore, the equation of water vapor permeability is constant or changes linearly or exponentially.

It is supposed that vapor permeability increases or stays constant when vapor content of air increases. Therefore, the first derivative for the equation of mass flow must grow continuously or be constant. Equation of mass flow must be zero when ν_2 is equal to ν_1. In this case, there is no potential to cause mass flow.

Thermal Conductivity Tests

Thermal conductivities of studied materials were measured with a heat flow meter. The apparatus used meets the requirements of ASTM and ISO standards (ASTM 1998; ISO 1991.) The apparatus consists of two parallel heat flux sensors that have been laminated to flat aluminium plates. The test specimen is set between the plates. When there is a temperature difference between plates, a heat flow from the warmer

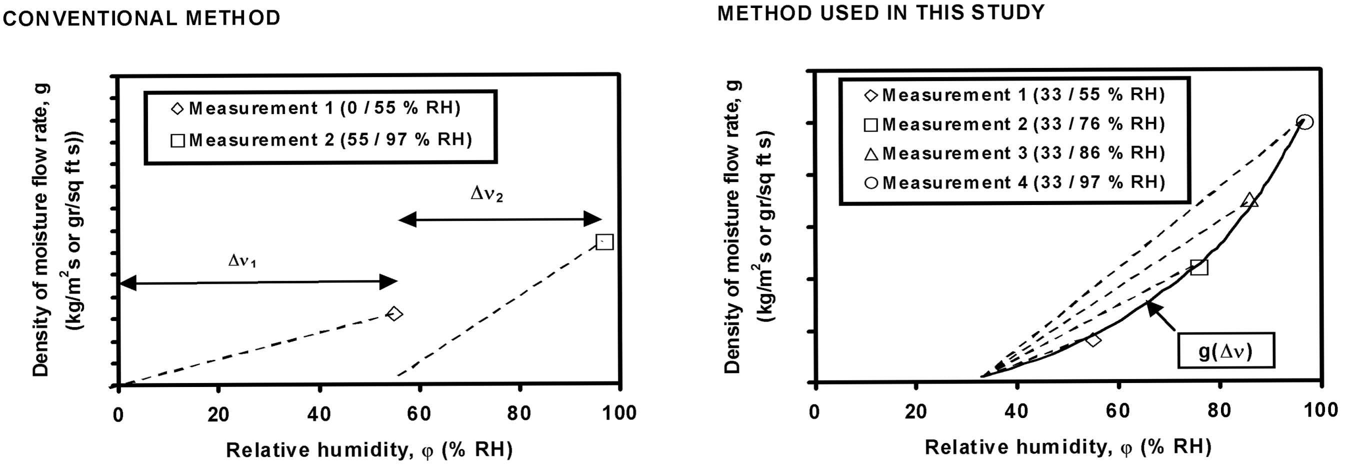

Figure 2 *Difference between conventional method and method used in this study to determine water vapor transmission properties (Mikkilä 2001). Ends of dashed lines represent relative humidities outside and inside the cup. Δv is the difference between water vapor contents inside and outside the cup.*

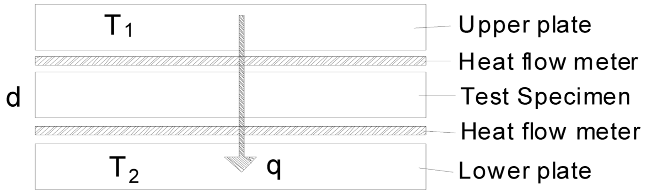

Figure 3 *Apparatus for measuring thermal conductivity.*

plate to the colder plate occurs. This heat flow is measured with heat flux sensors. The apparatus is shown in Figure 3.

Thermal conductivity can be calculated from Equation 7.

$$\lambda = \frac{q \cdot d}{(T_1 - T_2)} \tag{7}$$

where

λ = thermal conductivity (W/m·K or Btu·in./ft^2·h·°F)
q = density of heat flow (W/m^2 or Btu/ft^2·h)
d = thickness of test specimen (m or in.)
T_1 and T_2 = temperatures of warm and cold plates (K or °F)

In the material tests, the direction of heat flow was vertical. The temperature difference between the plates was 20°C (68°F), and the upper plate was warmer (downward heat flow) The direction of heat flow is a very essential variable when measuring damp materials. When the heat flow meter apparatus is running, moisture moves toward the colder plate. If the upper plate is colder, i.e., heat flow direction is upward, moisture could condense to the upper plate and fall down because of gravity. Thereafter, the fallen water droplets would evaporate and the moisture would move to the cold plate, and the same process, with phase changes contributing additional heat transfer to the results, would go on.

Test specimens were positioned in certain relative humidity conditions to achieve an equivalent moisture equilibrium. Relative humidities used were 33%, 65%, 86%, and 97%. Measurements were done at mean temperatures of –10°C, 0°C, +10°C, and +20°C (14°F, 32°F, 50°F, and 68°F). The average duration of one measurement was four hours for mineral wool products and ca. 72 h for other products. This was needed to reach thermal equilibrium.

TEST RESULTS

Water Vapor Transmission Tests

After measuring mass flows in all circumstances, equations of mass flow were determined for every material as a function of water vapor content (see Equation 5.) This equation was differentiated to have an equation of water vapor permeability. The calculated results are presented in this section.

Test results from water vapor transmission tests are shown in Tables 2 to 9 and Figures 4 to 10. The results have been presented as vapor permeabilities with regard to partial vapor pressure (δ_p) except for membranes, papers, bitumen felt, and polyethylene foil. For these materials, vapor permeance with regard to partial vapor pressure (W_p) is used. This is due to difficulties of controlling thickness of thin products. Values for material F2 are presented in a separate table (Table 10) because the values are of a different order of magnitude than other thin products. The materials that had constant vapor permeability at a constant temperature are listed in Tables 8 and 9.

Some materials had constant water vapor permeability at one temperature, whereas at some other temperature it rose as a function of relative humidity. The mathematical model for water vapor permeability at certain temperature was chosen according to the best correlation factor found. Therefore, several materials appear in Tables 2-9, Figures 4-10, and Table 8 or 9.

For some material, water vapor permeability values, which are greater than water vapor permeability of air (195 E–12 kg/m·s·Pa at +23°C or 134 gr/ft^2 at 73°F), appear in the tables and figures. This happens easily when the exponential function of mass flow gives best correlation and material is relatively permeable. Values exceeding water vapor permeability of air are theoretical and should not be used in calculations.

Thermal Conductivity Tests

Measurement results of thermal conductivity tests are presented in Tables 10 to 13 and Figures 11 and 12. Thermal conductivity is expressed as a function of relative humidity, meaning the RH circumstances in the climate chamber where the specimens were conditioned before measurements.

In Figures 11 and 12, the effect of moisture for thermal conductivity is presented at +10°C (50°F) mean temperature to demonstrate the effect of moisture on thermal conductivity. In Figure 11, thermal conductivity of gypsum board and plywood are presented as a function of RH. In Figure 12, Thermal conductivity of hygroscopic thermal insulation materials, porous fiberboards, and cellulose-based board are presented. Thermal conductivities of mineral-wool-based products are not shown in the figures because the effect of moisture on thermal conductivity at hygroscopic range is negligible.

DISCUSSION

Water Vapor Transmission Tests

Different products used for similar purposes had very different behavior. This underlines the fact that measurements in different conditions are necessary when accurate hygrothermal calculations and dimensioning of shell structures are desired. Fitting the results to a mathematical model was problematic because choosing the model giving best correlation in a certain temperature did not give logical results. However, these results were published to give an impression of the difficulties of expressing material values. For example, materials F2 and F4 were difficult to fit to any curves.

The most problematic materials to measure were very permeable and impermeable materials. Thermal insulation materials, which were most permeable for water vapor, are also most permeable for air. Therefore, convection can contribute to moisture transfer. When considering impermeable materials, imperfections in assembling the cup with improper sealing of the specimen can cause extra moisture leaks, leading to greater values of water vapor permeability than are is real.

Material values were at the same magnitude as in earlier studies (Tye 1993; Hedenblad 1996; Kumaran 1996.) This indicates that the cup method is suitable for different materials in several RH and temperature conditions.

Table 2. Water Vapor Permeabilities at +23°C (73°F) and Different Relative Humidities

Material ID	RH 35%		RH 50%		RH 70%		RH 90%	
	δ_p 10^{-12} kg/ m·s·Pa	δ_p gr/ft^2·h·Hg	δ_p 10^{-12} kg/ m·s·Pa	δ_p gr/ft^2·h·Hg	δ_p 10^{-12} kg/ m·s·Pa	δ_p gr/ft^2·h·Hg	δ_p 10^{-12} kg/ m·s·Pa	δ_p gr/ft^2·h·Hg
B4	2.4	1.7	2.4	1.7	4.3	3.0	11	7.4
W9	1.4	1.0	1.4	1.0	1.5	1.0	1.5	1.0
W10	0.9	0.6	0.9	0.6	2.1	1.4	6.2	4.3
I1	120	85	120	85	250	170	-	-
I2	130	88	130	88	250	170	-	-
I3	110	79	110	79	220	150	-	-
I4	120	83	120	83	220	150	-	-
I5	120	81	120	81	210	140	-	-
I6	80	56	81	56	110	76	-	-
I7	72	50	72	50	80	56	-	-

Table 3. Water Vapor Permeances at +23°C (73°F) and Different Relative Humidities

Material ID	RH 35%		RH 50%		RH 70%		RH 90%	
	W_p 10^{-9} kg/ m^2·s·Pa	W_p gr/ft^2· h·in.·Hg	W_p 10^{-9} kg/ m^2·s·Pa	W_p gr/ft^2· h·in.·Hg	W_p 10^{-9} kg/ m^2·s·Pa	W_p gr/ft^2· h·in.·Hg	W_p 10^{-9} kg/ m^2·s·Pa	W_p gr/ft^2· h·in.·Hg
F2	5.7	100	7.5	130	-	-	-	-
F3	0.78	14	1.1	19	1.6	28	-	-
F4	0.62	11	0.9	15	1.2	21	1.6	-
F5	1.4	25	1.4	25	2.5	44	-	-
F6	1.3	23	1.3	23	2.0	35	-	-
F7	0.5	8.2	0.5	8.2	0.6	10	1.2	-
F8	1.6	28	1.6	28	2.2	39	-	-
F9	1.3	23	1.3	23	1.7	30	-	-
F10	0.02	0.3	0.01	0.3	0.01	0.4	0.01	-
F13	0.68	12	0.70	12	1.2	21	-	-

Table 4. Water Vapor Permeabilities at +5°C (41°F) and Different Relative Humidities

Material ID	RH 35%		RH 50%		RH 70%		RH 90%	
	δ_p 10^{-12} kg/ m·s·Pa	δ_p gr/ft^2·h·Hg	δ_p 10^{-12} kg/ m·s·Pa	δ_p gr/ft^2·h·Hg	δ_p 10^{-12} kg/ m·s·Pa	δ_p gr/ft^2·h·Hg	δ_p 10^{-12} kg/ m·s·Pa	δ_p gr/ft^2·h·Hg
B2	3.7	2.5	4.2	2.9	4.9	3.4	5.5	3.8
B3	0.68	0.5	0.95	0.7	1.3	0.9	1.7	1.2
B4	3.5	2.4	3.5	2.4	4.6	3.2	10	6.9
W1	21	15	21	15	39	27	-	-
W8	1.3	0.9	1.3	0.9	1.4	1.0	2.5	1.7
W10	1.1	0.8	1.1	0.8	3.1	2.1	9.8	6.7

Table 5. Water Vapor Permeances at +5°C (41°F) and Different Relative Humidities

Material ID	RH 35%		RH 50%		RH 70%		RH 90%	
	W_p 10^{-9} kg/ $m^2 \cdot s \cdot Pa$	W_p gr/ft^2· h·in.·Hg	W_p 10^{-9} kg/ $m^2 \cdot s \cdot Pa$	W_p gr/ft^2· h·in.·Hg	W_p 10^{-9} kg/ $m^2 \cdot s \cdot Pa$	W_p gr/ft^2· h·in.·Hg	W_p 10^{-9} kg/ $m^2 \cdot s \cdot Pa$	W_p gr/ft^2· h·in.·Hg
F3	1.1	19	1.1	19	1.1	19	1.1	19
F5	1.2	21	1.2	22	7.5	130	-	-
F6	1.9	33	1.9	33	4.0	70	-	-
F8	1.5	26	1.5	26	3.9	68	-	-
F9	1.3	23	1.3	23	1.9	33	-	-
F13	0.6	10	0.6	10	2.5	44	-	-
F15	10	170	23	400	-	-	-	-

Table 6. Water Vapor Permeabilities at –10°C (14°F) and Different Relative Humidities

Material ID	RH 35%		RH 50%		RH 70%	
	δ_p 10^{-12} kg/m·s·Pa	δ_p gr/ft^2·h·Hg	δ_p 10^{-12} kg/m·s·Pa	δ_p gr/ft^2·h·Hg	δ_p 10^{-12} kg/m·s·Pa	δ_p gr/ft^2·h·Hg
B2	4.1	2.8	4.1	2.8	4.2	2.9
B3	0.3	0.2	0.7	0.5	1.2	0.8
B4	2.9	2.0	2.9	2.0	5.1	3.5
W8	0.9	0.6	1.1	0.8	1.4	1.0
W10	1.5	1.0	1.5	1.0	1.8	1.2

Table 7. Water Vapor Permeances at –10°C (14°F) and Different Relative Humidities

Material ID	RH 35%		RH 50%		RH 70%	
	W_p 10^{-9} kg/m^2·s·Pa	W_p gr/ft^2· h·in.·Hg	W_p 10^{-9} kg/m^2·s·Pa	W_p gr/ft^2· h·in.·Hg	W_p 10^{-9} kg/m^2·s·Pa	W_p gr/ft^2· h·in.·Hg
F2	5.9	100	16	280	-	-
F4	0.8	14	0.8	14	0.8	14
F5	1.6	28	2.5	44	3.7	65
F6	1.2	21	1.3	23	5.4	94
F8	1.4	25	1.8	32	2.3	40
F9	1.2	21	1.3	23	1.5	26
F13	0.8	14	1.4	25	2.0	35
F15	8.4	150	11	190	-	-

Table 8. Water Vapor Permeabilities for Materials Having Linear Mass Flow Equation

Material ID	Temperature +23ºC (73ºF)		Temperature +5ºC (41ºF)		Temperature -10ºC (14ºF)	
	δ_p 10^{-12} m·s·Pa/kg	δ_p ft^2·h·Hg/gr	δ_p 10^{-12} m·s·Pa/kg	δ_p ft^2·h·Hg/gr	δ_p 10^{-12} m·s·Pa/kg	δ_p ft^2·h·Hg/gr
B1	29	20				
B2	5.1	3.5				
B3	1.2	0.8				
W1	25	17			22	15
W2	43	30	36	25	33	23
W3	140	96	140	98	120	82
W4	110	75	110	79	93	64
W5	140	93	130	92	110	78
W6	120	82	110	73	100	70
W7	100	67	89	61	83	57
W8	2.5	1.7				
W12	36	25	35	24	20	20
I1			150	100	130	90
I2			140	99	130	87
I3			120	84	110	79
I4			130	89	120	81
I5			130	90	120	83
I6			77	53	64	44
I7			68	47	59	41

Table 9. Water Vapor Permeances for Thin Products Having Linear Mass Flow Equation

Material ID	Temperature +23°C (73°F)		Temperature +5°C (41°F)		Temperature –10°C (14°F)	
	W_p 10^{-9} m·s·Pa/kg	W_p ft^2·h·Hg/gr	W_p 10^{-9} m·s·Pa/kg	W_p ft^2·h·Hg/gr	W_p 10^{-9} m·s·Pa/kg	W_p ft^2·h·Hg/gr
F1	2.3	40				
F2			9.6	170		
F3					1.1	19
F4			0.9	16		
F12	2.3	40	2.1	37	1.7	30
F13	0.05	0.9				
F14	0.006	0.1				
F15	8.7	150				

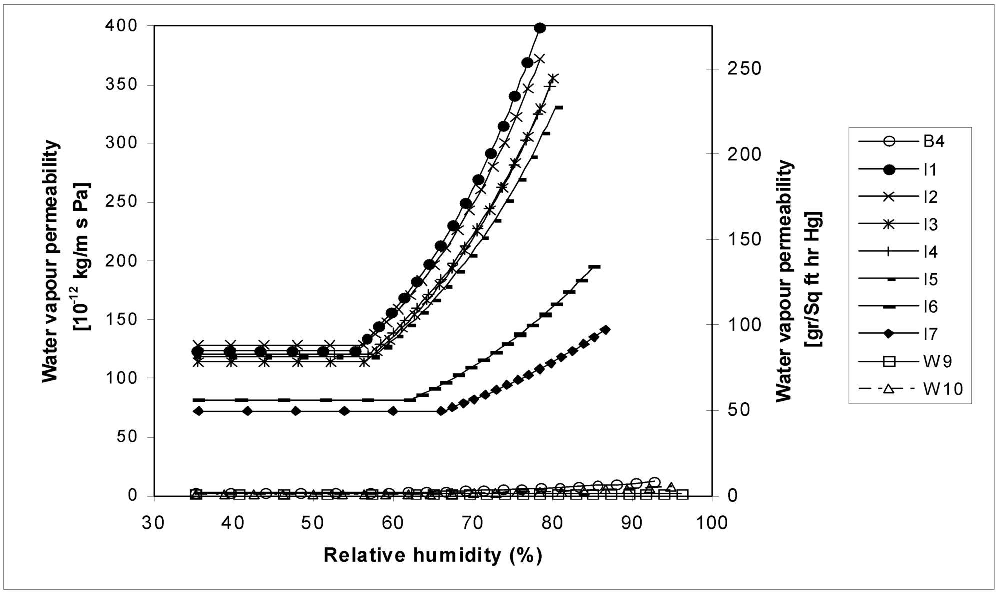

Figure 4 *Water vapor permeabilities* δ_p *at +23°C (73°F) temperature.*

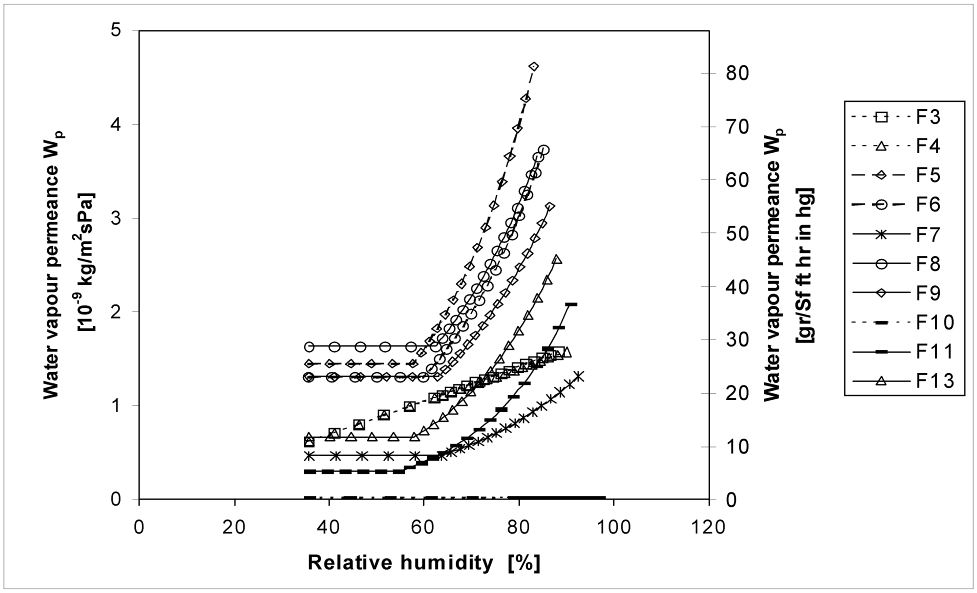

Figure 5 *Water vapor permeances* W_p *at +23°C (73°F) temperature for thin products (except F2).*

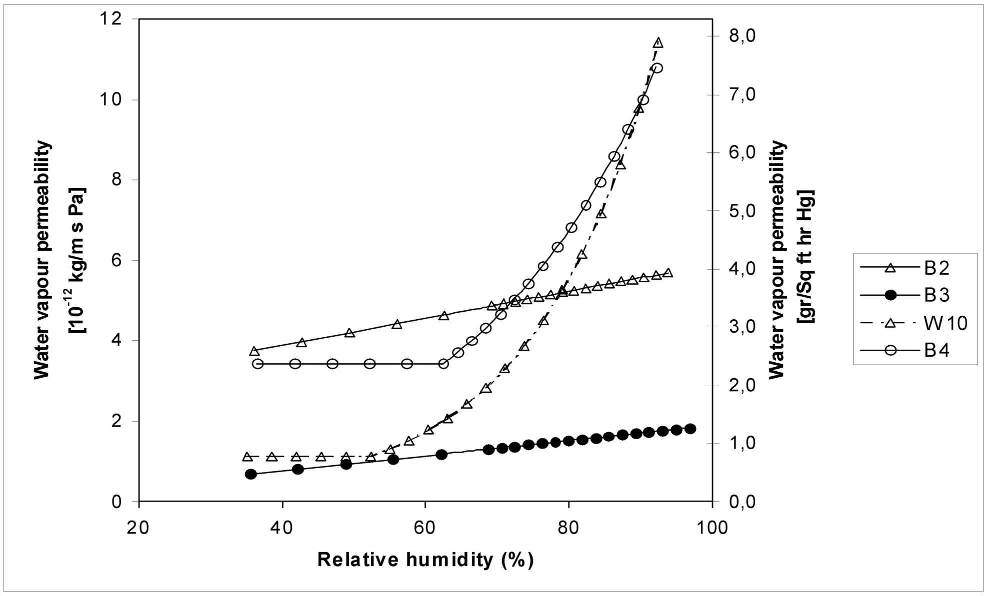

Figure 6 Water vapor permeabilities δ_p at +5°C (41°F) temperature.

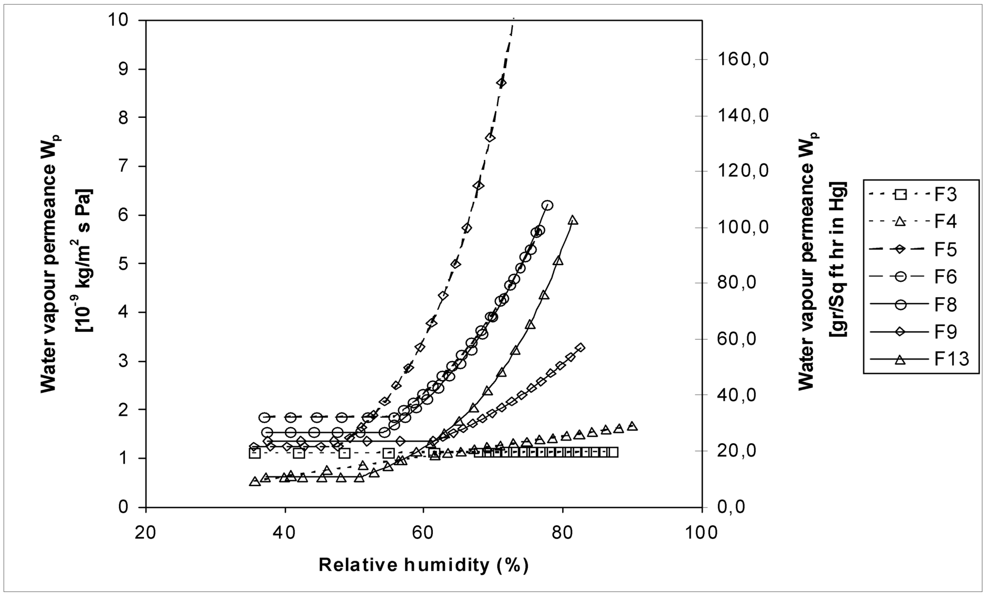

Figure 7 Water vapor permeances W_p at +5°C (41°F) temperature for thin products (except F2).

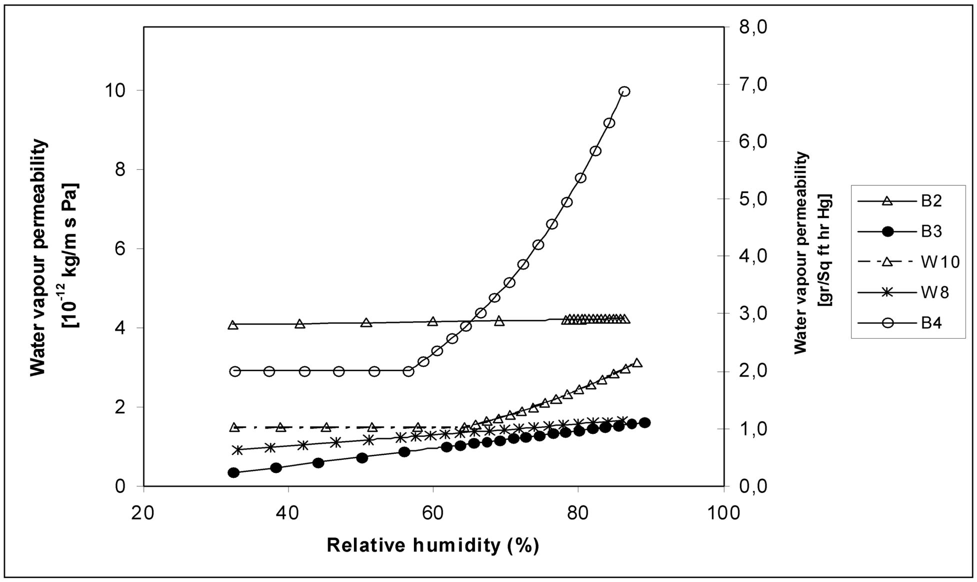

Figure 8 *Water vapor permeabilities* δ_p *at –10°C (14°F) temperature.*

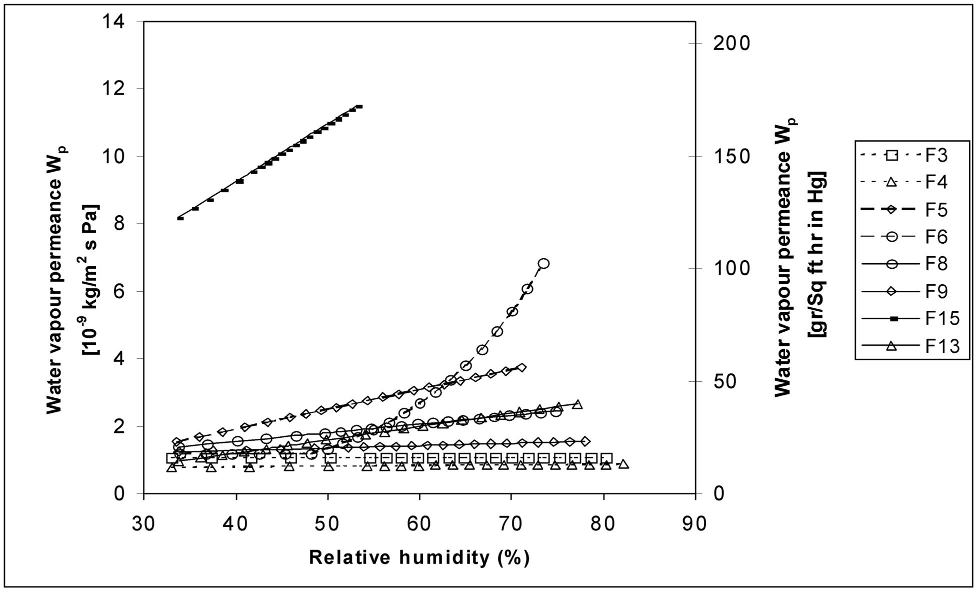

Figure 9 *Water vapor permeances* W_p *at –10°C (14°F) temperature for thin products (except F2).*

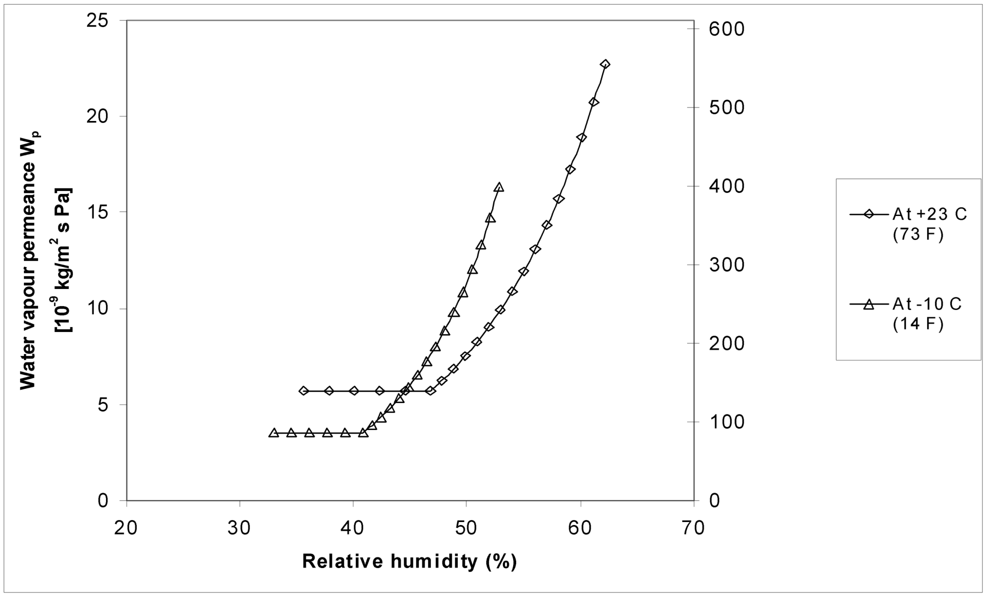

Figure 10 *Water vapor permeances* W_p *at various temperatures for diffusion membrane F2.*

Table 10. Thermal Conductivities After Conditioning at 33% Relative Humidity

Material	At –10°C (14°F)		At 0°C (32°F)		At 10°C (50°F)		At 20°C (68°F)	
ID	**W/m·K**	**Btu in./ h·ft^2·°F**	**W/m·K**	**Btu in./ h·ft^2·°F**	**W/m·K**	**Btu in./ h·ft^2·°F**	**W/m·K**	**Btu in./ h·ft^2·°F**
W1	0.17	1.2	0.18	1.2	0.19	1.3	0.20	1.4
W2	0.0472	0.327	0.0489	0.339	0.0504	0.350	0.0516	0.358
W3	0.0283	0.196	0.0295	0.205	0.0305	0.212	0.0317	0.220
W4	0.0288	0.200	0.0300	0.208	0.0310	0.215	0.0320	0.222
W5	0.0304	0.211	0.0308	0.214	0.0318	0.221	0.0331	0.230
W6	0.0301	0.289	0.0313	0.217	0.0324	0.225	0.0334	0.232
W7	0.0343	0.238	0.0353	0.245	0.0363	0.252	0.0375	0.260
W10	0.11	0.76	0.11	0.76	0.11	0.76	0.12	0.83
W12	0.0464	0.322	0.0480	0.333	0.0494	0.343	0.0508	0.352
I1	0.0332	0.230	0.0336	0.233	0.0351	0.243	0.0373	0.259
I2	0.0321	0.223	0.0323	0.224	0.0336	0.233	0.0354	0.245
I3	0.0342	0.237	0.0362	0.251	0.0371	0.257	0.0378	0.262
I4	0.0391	0.271	0.0405	0.281	0.0429	0.298	0.0443	0.307
I5	0.0333	0.231	0.0345	0.240	0.0359	0.249	0.0375	0.260
I6	0.0532	0.369	0.0546	0.379	0.0559	0.388	0.0575	0.399
I7	0.0506	0.351	0.0517	0.359	0.0531	0.368	0.0548	0.380

Table 11. Thermal Conductivities After Conditioning at 65% Relative Humidity

Material	At –10°C (14°F)		At 0°C (32°F)		At 10°C (50°F)		At 20°C (68°F)	
ID	W/m·K	Btu in./ h·ft^2·°F	W/m·K	Btu in./ h·ft^2·°F	W/m·K	Btu in./ h·ft^2·°F	W/m·K	Btu in./ h·ft^2·°F
W1	0.17	1.2	0.18	1.2	0.19	1.3	0.20	1.4
W2	0.0487	0.337	0.0508	0.352	0.0520	0.361	0.0534	0.370
W3	0.0282	0.196	0.0294	0.204	0.0305	0.212	0.0317	0.220
W4	0.0289	0.200	0.0302	0.209	0.0313	0.217	0.0324	0.225
W5	0.0294	0.204	0.0307	0.213	0.0319	0.221	0.0331	0.230
W6	0.0299	0.207	0.0315	0.218	0.0326	0.226	0.0334	0.232
W7	0.0354	0.245	0.0365	0.253	0.0376	0.261	0.0387	0.268
W10	0.11	0.76	0.11	0.76	0.11	0.76	0.12	0.83
W12	0.0476	0.330	0.0494	0.342	0.0512	0.355	0.0530	0.367
I1	0.0315	0.218	0.0332	0.230	0.0351	0.243	0.0369	0.256
I2	0.0306	0.212	0.0320	0.222	0.0336	0,233	0.0351	0.243
I3	0.0348	0.241	0.0361	0.250	0.0373	0.259	0.0382	0.265
I4	0.0410	0.284	0.0426	0.296	0.0440	0.305	0.0457	0.317
I5	0.0341	0.237	0.0354	0.246	0.0366	0.254	0.0378	0.262
I6	0.0554	0.384	0.0568	0.394	0.0577	0.400	0.0595	0.413
I7	0.0524	0.363	0.0539	0.374	0.0551	0.382	0.0567	0.393

Table 12. Thermal Conductivities after Conditioning at 86% Relative Humidity

Material	At –10°C (14°F)		At 0°C (32°F)		At 10°C (50°F)		At 20°C (68°F)	
ID	W/m·K	Btu in./ h·ft^2·°F	W/m·K	Btu in./ h·ft^2·°F	W/m·K	Btu in./ h·ft^2·°F	W/m·K	Btu in./ h·ft^2·°F
W1	0.18	1.2	0.19	1.3	0.20	1.4	0.21	1.5
W2	0.0492	0.341	0.0536	0.372	0.0553	0.383	0.0568	0.394
W3	0.0283	0.196	0.0293	0.203	0.0305	0.212	0.0316	0.219
W4	0.0293	0.203	0.0301	0.209	0.0311	0.216	0.0322	0.223
W5	0.0301	0.209	0.0309	0.214	0.0321	0.223	0.0328	0.227
W6	0.0302	0.209	0.0314	0.218	0.0325	0.225	0.0336	0.233
W7	0.0364	0.252	0.0375	0.260	0.0386	0.268	0.0397	0.275
W10	0.12	0.83	0.12	0.83	0.12	0.83	0.13	0.90
W12	0.0496	0.344	0.0520	0.361	0.0543	0.377	0.0565	0.392
I1	0.0317	0.220	0.0335	0.232	0.354	0.245	0.0372	0.258
I2	0.0303	0.210	0.0318	0.221	0.0333	0.231	0.0349	0.242
I3	0.0394	0.273	0.0407	0.282	0.0415	0.288	0.0421	0.292
I4	0.0420	0.291	0.0442	0.307	0.0468	0.324	0.0493	0.342
I5	0.0355	0.246	0.0370	0.257	0.0380	0.263	0.0385	0.267
I6	0.0578	0.401	0.0595	0.413	0.0619	0.429	0.0638	0.442
I7	0.0544	0.377	0.0560	0.388	0.0574	0.398	0.0589	0.408

Table 13. Thermal Conductivities after Conditioning at 97% Relative Humidity

Material	At –10°C (14°F)		At 0°C (32°F)		At 10°C (50°F)		At 20°C (68°F)	
ID	W/m·K	Btu in./ h·ft^2·°F	W/m·K	Btu in./ h·ft^2·°F	W/m·K	Btu in./ h·ft^2·°F	W/m·K	Btu in./ h·ft^2·°F
W1	0.19	1.3	0.20	1.4	0.21	1.5	0.22	1.5
W2	0.0512	0.355	0.0528	0.366	0.0541	0.375	0.0565	0.392
W3	0.0285	0.198	0.0293	0.203	0.0307	0.213	0.0320	0.222
W4	0.0291	0.202	0.0299	0.207	0.0315	0.218	0.0326	0.226
W5	0.0302	0.209	0.0310	0.215	0.0323	0.224	0.0332	0.230
W6	0.0303	0.210	0.0312	0.216	0.0327	0.227	0.0338	0.234
W7	0.0377	0.261	0.0388	0.269	0.0399	0.277	0.0410	0.284
W10	0.12	0.83	0.12	0.83	0.13	0.90	0.13	0.90
W12	0.0504	0.350	0.0521	0.361	0.0329	0.228	0.0542	0.376
I1	0.0328	0.227	0.0338	0.234	0.0353	0.245	0.0375	0.260
I2	0.0310	0.215	0.0323	0.224	0.0337	0.234	0.0355	0.246
I3	0.0404	0.280	0.0417	0.289	0.0424	0.294	0.0441	0.306
I4	0.0431	0.299	0.0445	0.309	0.0459	0.318	0.0473	0.328
I5	0.0376	0.261	0.0391	0.271	0.0405	0.281	0.0421	0.292
I6	0.0632	0.438	0.0664	0.460	0.0682	0.473	0.0701	0.486
I7	0.0567	0.393	0.0582	0.404	0.0599	0.415	0.0621	0.431

Thermal Conductivity Tests

Because no material measured in this test series was a closed-cell product with cell gases, the correlation between temperature and heat flow should be linear. Linearity was evident, especially with mineral wool, where phase changes of water vapor did not affect heat flow.

Mineral wool products did not react to rise of RH because they were nonhygroscopic.Wood-based products, instead, had a slight rise in thermal conductivity when RH increased.

Measurements at low temperatures should be continued because temperature conditions were not at extremes.

CONCLUSIONS

Changes in material properties due to humidity and temperature have to be considered in building design and construction because there are products that have very different values in different conditions. In many situations, materials may perform in an even more favorable way than expected. For example, water vapor permeance of sheathing is critical in cold climates, where the direction of diffusion is from inside to outside. Therefore, there is a certain lower limit for water vapor permeance of sheathing. This limit depends on climate conditions, moisture content inside the house, and characteristics of the wall/ roof/ subfloor assembly. Water vapor permeance of many products tends to increase when relative humidity increases. In this situation, increasing permeance of sheathing gives an extra margin of safety. This phenomen was met also in this study, especially when measuring wood-based materials and paper-based sheets. On the other hand, when considering an interior side of the building, the permeance of materials must not increase because this would accelerate diffusion through the building shell. This would lead to moisture problems if the other side of the assembly (sheathing) was not permeable enough.

Variations in material properties due to production and defects in construction work were not studied in this research, but they shall never be neglected.

In thermal conductivity tests, thermal conductivity seemed to change linearly also in temperatures below 0°C (32°F), when moisture conditions are clearly below capillary range. Accuracy of extrapolations for temperatures below measuring range (below –10°C, i. e., below 14°F) has not been studied. Extrapolation of test results is not recommended for scientific studies because of the little amount of measurement points in low temperatures.

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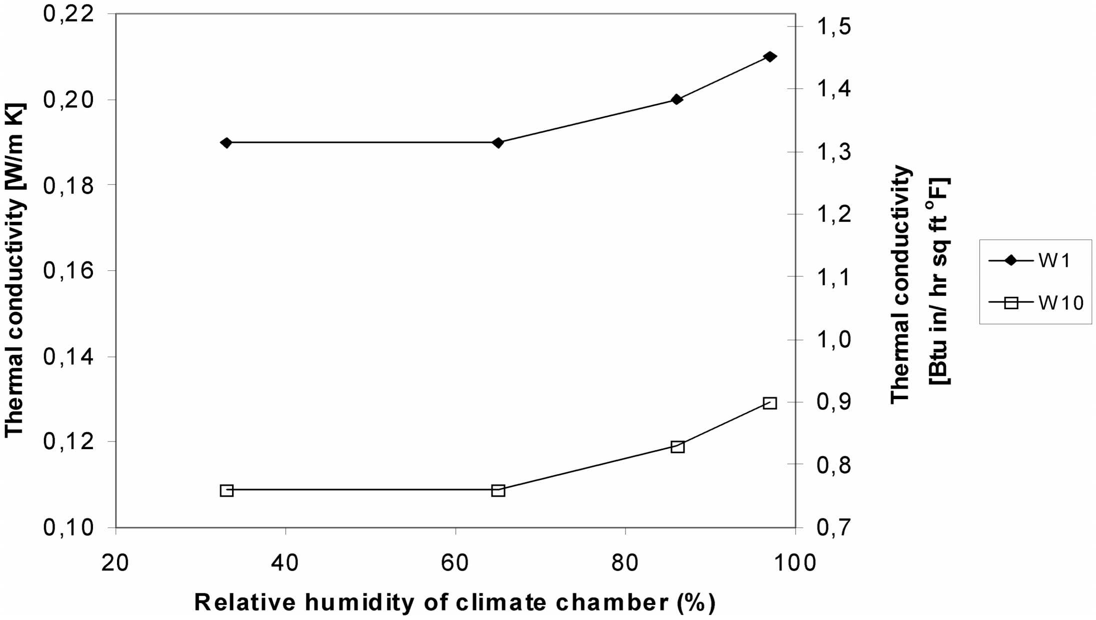

Figure 11 *Thermal conductivities of gypsum board (W1) and plywood (W10) as a function of relative humidity at +10°C (50°F) mean temperature.*

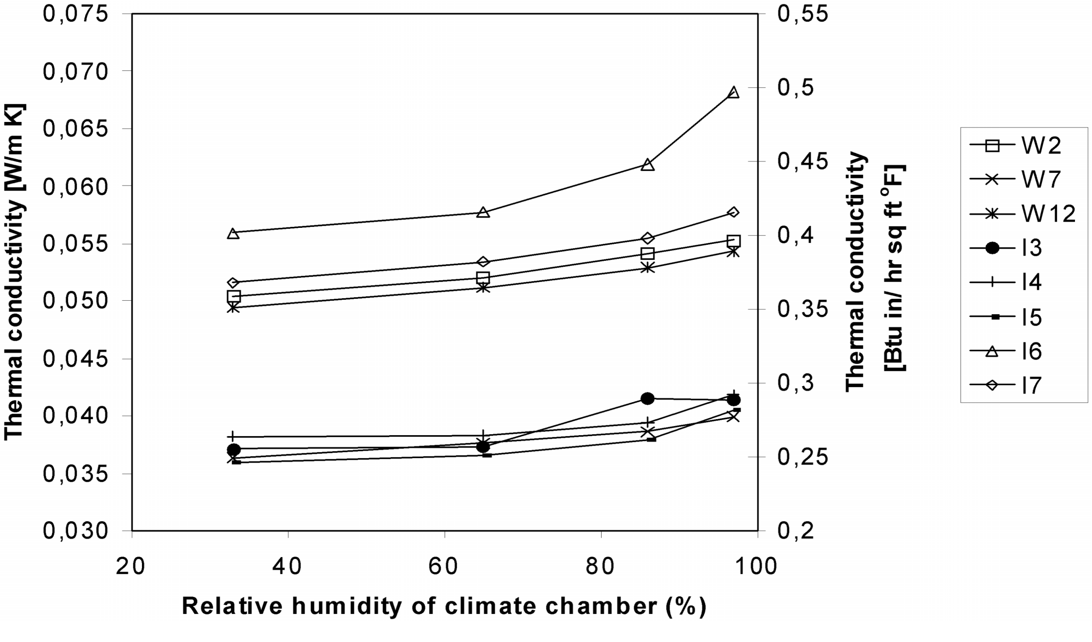

Figure 12 *Thermal conductivities of porous fiberboards (W2 and W12), cellulose board (W7), cellulose blanket (I3), loose-fill cellulose insulation (I4), flax blanket (I5), sawdust (I6), and chipping (I7) as a function of relative humidity at +10°C (50°F) mean temperature.*

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