Trends and Anomalies in Hygrothermal Material Properties from the ASHRAE 1696 Research Program

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ABSTRACT

Budget and time constraints preclude the determination of specific material properties for most energy and hygrothermal design, simulation and modeling tasks. Practitioners rely heavily on material property data included in computer program databases and/or from published resources such as Chapter 26 of the ASHRAE Handbook of Fundamentals (HOF), which haslong been one of the best and preferred industry resources for thermal and moisture properties of insulations and building materials. This paper presents an overview of the ASHRAE 1696 Research Project, "Thermal, Moisture and Air Transport Property Values for New Building and Insulating Materials." Subject materials (15 new and 9 updated) are addressed; test methods for 10 hygrothermal material properties are summarized; and finally, trends and anomalies are highlighted.

INTRODUCTION

When designing, modelling, and commissioning a building, the choice of materials is a core activity, with implications for human comfort, energy consumption, and the service life of a building. Material selection is driven in part by the known or assumed hygrothermal properties of materials. Therefore, access to accurate and up-to-date material property data is essential. Practioners rely on existing material property databases to source this information. Publications such as ASRHAE's Handbook of Fundamentals (HOF), a comprehensive and longstanding industry resource, are a key authority for detailed data on building material hygrothermal properties.

However, establishing material property values is challenging. Resource considerations often impede regular updating of these databases: the availability of resources, budget limitations, and time place constraints on these activities. Manufacturers regularly refine existing products or develop new ones. The speed of market uptake for these materials varies widely and depends on current design and construction trends and needs. As well, testing and characterizing material properties can take months to years, in which time new materials are adopted by industry.

Despite these barriers, ASHRAE has dedicated resources to updating HOF hygrothermal properties database twice in the last 20 years. The 2009 edition of the HOF was significantly updated based on the findings of RP-905. This project resulted in a deep review and revision of the existing HOF hygrothermal database (McGowan 2007). Suggestions from RP-905 addressed the need for data on new materials, such as glass-mat exterior sheathing, and reasoned that data for some represented materials, such as fiberboard and particleboard, may be outdated. Insights from this project provided a core focus for the current RP-1696 project. Prior to RP-905, RP-1018 presented new

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hygrothermal data for 38 materials. Results were summarized in a major report for ASHRAE (Kumaran 2002), and a summary for NRC-IRC (Kumaran 2006). Other key ASHRAE projects include RP-1235 and RP-1365, which provided recommendations that were adopted by and integrated into RP-1696 (Derome, Karagiozis, and Carmeliet 2010; Roppel, Lawton, and Norris 2012)

Testing for RP-1696, titled *Thermal, Moisture, and Air Transport Property Values for New Building and Insulating Materials*, began in 2016. The project was undertaken to determine the hygrothermal properties for 9 updated and 15 new materials commonly used in construction. The material properties of interest included thermal conductivity, water vapor permeance, hygroscopic sorption isotherms, and air permeance, among others. These properties were determined using well-known ASTM and ISO standard test methods. Detailed results for RP-1696 will be provided in a major report. In this paper, we present an overview of the RP-1696 project, with a summary of the project approach and methodology, as well as an exploration of the more interesting findings. The new hygrothermal property values are contextualized within the existing data and alternate literature, with the goal of defining trends and highlighting anomalies in the results.

METHODS

Subject Materials

The materials tested included a selection of 9 updated and 15 new materials. Seven major material families were defined, each with a minimum of two material sub-groups. These are summarized in Table 1. Ultimately, more than 60 distinct materials from 24 manufacturers were tested. Materials were either donated by manufacturers or distributors, or purchased from local hardware stores. Roofing and stucco materials were prepared in a contractor's shop, using materials obtained either from the contractor or from a manufacturer.

Table 1. Test Material Families and Sub-Groups.

Family	Sub-Group
Wood- based products	Particleboard, Medium- and High-Density Fiberboard
Roofing and Self-Adhering Membrane	Two-ply SBS, Single-ply EPDM, Single-ply TPO, SA Membrane
Water-Resistant Barrier (WRB) and Backerboard	Fluid-applied WRBs, Roof Underlayment, Backerboard
Stucco	3-coat Cement Finish, 3-coat Acrylic Finish 3-coat Elastomeric Finish
Cladding	Fiber-cement Lap and Panel siding, Brick, Clay tile
Insulation	Aerogel, Carpet Pad, Slag wool, Acoustic Tile
Gypsum	1/2" Glass-Mat Gypsum, 5/8" Glass-Mat Gypsum

Hygrothermal Properties

A set of nine hygrothermal properties were selected. These were: thermal conductivity, specific heat, density, air permeance, water vapor permeance, liquid diffusivity, sorption isotherms, solar absorptivity and thermal emissivity. Historically, all properties, except for solar absorptivity and thermal emissivity, are included in the HOF. The addition of solar absorption and thermal emission data highlights the importance of these values in building design and modelling. The solar absorption and thermal emissivity data is not included in this summary paper. For all methods, the associated ASTM and ISO standards are listed in Table 2. The solar absorptivity and thermal emissivity properties were determined by Dr. Michael Collins at the University of Waterloo, in Waterloo, Canada. All remaining testing was completed at RDH Building Science Laboratories, located in Waterloo, Canada.

Table 2. Material Properties and Related ASTM Standards

Material Property	ASTM Standard	Material Family
Thermal conductivity	ASTM C518	Wood-based materials, Backerboard, Cladding, Insulation, Gypsum
Density	ASTM D2395, ASTM D792	All
Air permeance	ASTM E2178, ASTM E2935	Wood-based materials, WRB, Gyspum
Water vapor permeance	ASTM E96	Wood-based materials, Roofing, WRB, Backerboard, Stucco, Cladding, Insulation, Gypsum
Liquid Diffusivity	ISO 15148	Wood-based materials, Roofing, WRB, Backerboard, Stucco, Cladding, Insulation, Gypsum
Sorption Isotherm	ASTM C1498, ASTM C1699	Wood-based materials, WRB, Backerboard, Stucco, Cladding, Insulation, Gypsum
Solar Absorptivity	ASTM E903	Roofing, Stucco, Cladding
Thermal Emissivity	ASTM E408	Roofing, Stucco, Cladding

TRENDS AND ANOMALIES

For materials with established hygrothermal values, a first comparison point was the current edition of the HOF (ASHRAE 2017). In most cases our test results tended to closely track existing values. The similarities between existing and newly determined values are discussed. However, not all values were in agreement. Where there were notable differences, potential sources of variation are discussed. Potential and known factors affecting these differences include: alterations to formulation, differences in test methods, natural inhomogeneity in materials, as well as others. Summaries of these discussions are provided where relevant, with the goal of providing insight into mechanisms and factors that affect the hygrothermal behavior of materials and may be important considerations for material manufacturers, as well as buildings designers, contractors, and maintenance personnel.

For materials not previously included in the HOF, the literature was explored for comparative data. Sources included manufacturer data, as well as academic and industry publications. Ideally, data from the manufacturer was compared to published data and RP-1696 test results. In many instances, the test results were close to, if not very similar to the manufacturer's results, validating the testing performed for RP-1696 as well as the manufacturer's own results.

Wood-Based Materials

Hardboards with two different densities (high- and medium-density), and particleboard (Table 1) were included in this category. These products were included based on recommendations from RP-905, which identified a need to produce updated hygrothermal values for wood-based materials, in particular for thermal conductivity (McGowan 2007). A brief literature search emphasizes the significant changes to the manufacturing processes and base-components for this product family, which includes the use of new adhesives and incorporation of different wood species. Regulatory factors, such as California Air Resources Board's (CARB) requirements for formaldehyde emissions in wood-panel products (California Air Resources Board 2019), have placed pressure on manufacturers to find alternatives that limit formaldehyde off-gassing indoors. This regulation underscores the shift in application for wood-based materials, noted in RP-905 (McGowan 2007), from exterior sheathing to almost exclusively interior furnishings. This shift has also affected manufacturing processes. Given these changes, it is likely that the hygrothermal behaviours of these materials have been altered.

Currently reported thermal conductivity values for hardboard and particleboard are for a mean temperature of 24ºC (75.2ºF) (ASHRAE 2017). Modern values for particleboard (Czajkowski et al. 2016; Sonderegger and Niemz 2009), and medium-density hardboard (Sonderegger and Niemz 2009; Zhou et al. 2013) were identified and are presented in Table 3. Where the mean test temperature for some, but not all, conductivity values. Lack of information about test temperatures is related to the methods used to determine thermal properties, which included transient and steady-state approaches. For RP-1696, all wood-based products were tested at mean temperatures of 10ºC and 24ºC (50ºF and 75.2ºF) using the steady-state method described in ASTM C518 (ASTM 2015). These results are also presented in Table 3. This side by side comparison of data shows there are no relevant differences between RP-1696 test results, and the other data. In spite of the different methodologies that were applied, reported results range from 0.097 to 0.196 W/m·K (0.056 to 0.113 Btu·in/h·ft2·°F) (Czajkowski et al. 2016; Sonderegger and Niemz 2009; Zhou et al. 2013). The highest value is for a medium-density panel, and the lowest for a particleboard.

The moisture response of wood-based materials, however, exhibited significant variations in results. The water vapor permeance values for particleboard in the HOF are less than half those determined through testing. At the 90% RH test condition, the water vapor permeance for modern particleboard was more than three times higher than currently published values (1182 ng/Pa·s·m^2 vs 490 ng/Pa·s·m^2). It is worth noting that our data is the result of direct testing of samples at the different relative humidities. The data from Kumaran reported in the HOF is based on an analysis method that extrapolates values from test data (Kumaran 1998) and this may explain the differences. No updated water vapor permeance data was located.

The sorption properties for hardboard and particleboard were largely similar to previously reported data, although the moisture content of particleboard at high RH (i.e. above 95%) was double the reported value (110% MC at 95% RH vs 21.5% MC at 97.3% RH) (ASHRAE 2017). The difference in values for particleboard may be due to differences in density. Moisture saturation values for the hardboard materials are also nearly 30% higher than those reported. One explanation is that the new values were determined using the vacuum saturation method, whereas the reported values are for total saturation during immersion. Importantly, the single moisture content values taken from the literature (Zhou et al. 2013; Sonderegger and Niemz 2009; Czajkowski et al. 2016) are within range of the test values. Because these tests were conducted on newer materials, it is likely that the values will be similar. It is also worth noting that RP-1696 sorption isotherm values are similar across the three different materials, which, again, may be explained by the methods used.

There is no water absorption coefficient (A-value) currently reported for particleboard. We were unable to source information on this material property for standard particleboard materials, either from the literature or directly from manufacturer specification sheets. Products comparable to particleboard, such as plywood and oriented strand board, have similar reported values to those measured for particleboard (0.0042 and 0.0016 kg/m^2·$s^{1/2}$, respectively, vs. 0.0026 kg/m^2·$s^{1/2}$) (0.0009 and 0.0003 lb/ft^2·$s^{1/2}$, respectively, vs. 0.0005 lb/ft^2·$s^{1/2}$) (ASHRAE 2017). The A-value reported for hardboard (0.00072 kg/m^2·$s^{1/2}$; 0.0001 lb/ft^2·$s^{1/2}$) is, however, an order of magnitude lower than what was measured for modern hardboard (0.0024 and 0.0034 kg/m^2·$s^{1/2}$) (0.0005 and 0.0007 lb/ft^2·$s^{1/2}$) (ASHRAE 2017). The A-values may differ due to differences in material manufacturing and composition. The reader should note that the modern hardboard products were tested after conditioning at 30%, 50%, and 80% RH, on the through-thickness surface.

The proprietary composition of particleboard and hardboard varies significantly from one manufacturer to the next, making it challenging to confidently state what factors are affecting the test results. However, this does not prevent the consideration of potential influences. Wood species are diverse in their response to moisture. This is also true of binders and glues. The variation in composition is one factor likely influencing the broad range of values for the hygric and thermal data presented here. Given that the dominant use for wood-based products is now indoors, it is no longer as important to treat the materials for water-resistance, which may also account for some of these differences. The minimal difference in thermal conductivity values would be expected as different adhesives, binders, and wood species only have a minimal effect on this property.

Table 3. Particleboard and Hardboard Material Properties (SI)

Material Density† Thickness††	Thermal Conductivity		Water Vapor Permeance		Air Permeance	Sorption Isotherm		Water Absorption Coefficient	
	Mean Temperature Setpoint	W/mK	Mean RH Setpoint	ng/Pa·s·m^2	Lps/m^2 at 75 Pa	RH Condition Setpoint	(% MC)	RH Condition Setpoint	kg/(m^2·s$^{0.5}$)
Particleboard 663 kg/m^3 13 mm	10°C	0.114 (±0.034)	15%	200 (±11)	0.004 (±8.4·10^{-5})	30%	4 (±2·10^{-4})	30%	0.0036 (±1·10^{-4})
	24°C	0.118 (±0.005)	25%	197 (±13)		50%	7 (±3·10^{-4})	50%	0.0026 (±1·10^{-5})
			65%	391 (±37)		80%	12 (±2·10^{-4})	80%	0.0028 (±2·10^{-4})
			75%	494 (±35)		90%	16 (±4·10^{-4})		
			90%	1182 (±57)		98%	58 (±2·10^{-2})		
			95%	1876 (±365)		100%	110 (±2·10^{-2})		
Particleboard* 634 kg/m^3 18 mm	24°C	0.109	N/A		N/A	N/A		N/A	
	N/A	0.113							
Particleboard** 648 kg/m^3 16.6 mm	10°C	0.1103	N/A		N/A	65%	10	N/A	
Hardboard 697 kg/m^3 16 mm	10°C	0.112 (±0.002)	15%	467 (±11)	0.011 (±3.7·10^{-5})	30%	3 (±1·10^{-6})	30%	0.0039 (±3·10^{-4})
	24°C	0.116 (±0.002)	25%	476 (±14)		50%	6 (±9·10^{-5})	50%	0.0034 (±4·10^{-5})
			65%	720 (±14)		80%	11 (±2·10^{-4})	80%	0.0036 (±2·10^{-4})
			75%	688 (±14)		90%	15 (±4·10^{-4})		
			90%	1095 (±36)		98%	39 (±1·10^{-2})		
			95%	2307 (±155)		100%	149 (±7·10^{-2})		
Hardboard** 744 kg/m^3 16.4 mm	10°C	0.107	N/A		N/A	65%	8	N/A	
Hardboard*** 796 kg/m^3 2.6 mm	25°C	0.196	N/A		N/A	65%	8	N/A	
Hardboard 875 kg/m^3 5 mm	10°C	0.13 (±0.004)	15%	786 (±20)	0.018 (±9.1·10^{-5})	30%	3 (±1·10^{-4})	30%	0.0025 (±1·10^{-5})
	24°C	0.135 (±0.004)	25%	726 (±14)		50%	5 (±2·10^{-4})	50%	0.0024 (±3·10^{-5})
			65%	1244 (±31)		80%	10 (±1·10^{-4})	80%	0.0024 (±5·10^{-5})
			75%	1251 (±25)		93.5%	14 (±2·10^{-4})		
			90%	2723 (±216)		98%	38 (±5·10^{-3})		
			95%	5070 (±340)		100%	124 (±4·10^{-2})		

† Density values, as determined by the lab using a modified ASTM D2395 method A approach
†† Measured thickness
* (Czajkowski et al. 2016)
** (Sonderegger and Niemz 2009)
*** (Zhou et al. 2013)

Table 3. Particleboard and Hardboard Material Properties (IP)

Material Density† Thickness††	Thermal Conductivity		Water Vapor Permeance		Air Permeance	Sorption Isotherm		Water Absorption Coefficient	
	Mean Tempe-rature Setpoint	Btu·in/h·ft^2·°F	Mean RH Setpoint	Perm	gpm/ft^2 at 0.0075 bar	RH Condition Setpoint	(% MC)	RH Condition Setpoint	lb/(ft^2·$s^{0.5}$)
Particleboard 41.4 lb/ft^3 0.51 inches	50ºF	0.79 (±0.02)	15%	3 (±0.2)	0.006 (±1.2·10^{-4})	30%	4 (±2·10^{-4})	30%	7.38 * 10^{-6} (±2·10^{-5})
	75.2ºF	0.82 (±0.003)	25%	3 (±0.2)		50%	7 (±3·10^{-4})	50%	5.33 * 10^{-6} (±2·10^{-4})
			65%	7 (±0.6)		80%	12 (±2·10^{-4})	80%	5.74 * 10^{-6} (±4·10^{-5})
			75%	9 (±0.6)		90%	16 (±4·10^{-4})		
			90%	21 (±1)		98%	58 (±2·10^{-2})		
			95%	33 (±6)		100%	110 (±2·10^{-2})		
Particleboard* 39.6 lb/ft^3 0.71 inches	75.2ºF	0.75	N/A		N/A	N/A		N/A	
	N/A	0.78							
Particleboard** 40.5 lb/ft^3 0.65 inches	50ºF	0.67	N/A		N/A	65%	10	N/A	
	N/A	0.76							
Hardboard 43.6 lb/ft^3 0.63 inches	50ºF	0.78 (±0.001)	15%	8 (±0.2)	0.016 (±5.4·10^{-5})	30%	3 (±1·10^{-6})	30%	8 * 10^{-6} (±6·10^{-5})
	75.2ºF	0.80 (±0.001)	25%	8 (±0.2)		50%	6 (±9·10^{-5})	50%	6.97 * 10^{-6} (±8·10^{-6})
			65%	13 (±0.2)		80%	11 (±2·10^{-4})	80%	7.38 * 10^{-6} (±4·10^{-5})
			75%	12 (±0.2)		90%	15 (±4·10^{-4})		
			90%	19 (±0.6)		98%	39 (±1·10^{-2})		
			95%	40 (±3)		100%	149 (±7·10^{-2})		
Hardboard** 46.5 lb/ft^3 0.65 inches	50ºF	0.74	N/A		N/A	65%	8	N/A	
Harboard*** 49.8 lb/ft^3 0.1 inches	77ºF	0.74	N/A		N/A	65%	8	N/A	
Hardboard 54.7 lb/ft^3 0.2 inches	50ºF	0.9 (±0.002)	15%	14 (±0.3)	0.027 (±1.3·10^{-4})	30%	3 (±1·10^{-4})	30%	5.13 * 10^{-6} (±2·10^{-6})
	75.2ºF	0.94 (±0.002)	25%	13 (±0.2)		50%	5 (±2·10^{-4})	50%	4.92 * 10^{-6} (±6·10^{-6})
			65%	22 (±0.5)		80%	10 (±1·10^{-4})	80%	4.92 * 10^{-6} (±1·10^{-5})
			75%	22 (±0.4)		90%	14 (±2·10^{-4})		
			90%	48 (±4)		98%	38 (±5·10^{-3})		
			95%	89 (±6)		100%	124 (±4·10^{-2})		

† Density values, as determined by the lab using a modified ASTM D2395 method A approach
†† Measured thickness
* (Czajkowski et al. 2016)
** (Sonderegger and Niemz 2009)
*** (Zhou et al. 2013)

WRB Materials

A variety of water-resistant barriers (WRB) are available for use in construction. WRB come in different forms: self-adhering membranes, membranes that require the use of an adhesive, and fluid-applied membranes. The fluid-applied barriers are made using various base components, such as latex, asphalt, and silicone. This flexibility in chemical composition results in barriers with varied requirements in terms of application, applied thickness, curing time, and hygrothermal properties. Although the HOF provides data on various building papers and barriers, there are currently no fluid-applied WRB materials listed. RP-1235 identified a need to further characterize the behavior of these water-resistive barriers, particularly for calculations and modelling the effects of solar drive on vapor diffusion. To fill this gap, six unique liquid-applied WRB were tested for RP-1696; half were marketed as vapor impermeable and the other half as vapor permeable. The base chemistries were: latex, acrylic, silicone, asphalt, and silyl-terminated polyether (STPE).

Locating additional sources of WRB properties proved challenging. We were unable to locate alternate data sources, and thus used comparative data from manufacturers. All of the WRB products that were tested had detailed data specification sheets, which included air permeance and water vapor permeance values. RP-1696 test results and manufacturer data are listed in Table 4.

Table 4. Fluid-applied Water-resistant Barriers (SI)

Material Density[*]	Water Vapor Permeance (measured)		Water Vapor Permeance (manufacturer)[**]	Air Permeance		Water Absorption Coefficient	Sorption Isotherm	
	Mean RH Setpoint[**]	ng/Pa·s·m²	ng/Pa·s·m²	Lps/m² at 75 Pa Measured	Lps/m² at 75 Pa Manufacturer	$kg/m^2 \cdot s^{0.5}$	Mean RH Setpoint	% MC
Asphalt 899 kg/m³	25%	6 (±0.6)	1.02	0.0002	0.002	0.0004 $(\pm 1\cdot 10^{-4})$	50%	0.4 (±0.03)
	75%	333 (±11)						
	90%	502 (±19)					90%	2.4 (±0.05)
	95%	2060 (±198)						
Acrylic Polymer 1250 kg/m³	25%	14 (±0.5)	[A.]1.71	0.0003	0.01	0.0002 $(\pm 2\cdot 10^{-5})$	50%	0.05 (±0.02)
	75%	108 (±2)						
	90%	163 (±4)					90%	1.2 (±0.08)
	95%	516 (±46)						
Latex VI 1161 kg/m³	25%	5 (±0.4)	[A.]3.43	0.0002	PASS	0.000003 $(\pm 2\cdot 10^{-5})$	50%	0.01 (±0.02)
	75%	18 (±1)						
	90%	50 (±4)					90%	0.6 (±0.01)
	95%	75 (±9)						
Silicone 1214 kg/m³	25%	125 (±7)	538	0.0002	0.003	0.0006 $(\pm 3\cdot 10^{-4})$	50%	-1.2 (±0.2)
	75%	150 (±8)						
	90%	301 (±41)					90%	1.8 (±0.09)
	95%	303 (±6)						
STPE 1291 kg/m³	25%	173 (±2)	[B.]1030	0.0002	0.0009	0.002 $(\pm 2\cdot 10^{-3})$	50%	0.6 (±0.1)
	75%	513 (±38)						
	90%	892 (±39)					90%	1.6 (±0.04)
	95%	1379 (±17)						
Latex VP 1384 kg/m³	25%	14 (±3)	[B.]>575	0.0002	0.001	0.001 $(\pm 4\cdot 10^{-5})$	50%	0.1 (±0.01)
	75%	1205 (±22)						
	90%	2966 (±96)					90%	0.8 (±0.1)
	95%	4905 (±83)						

VP and VI describe the manufacturer's labelling for the products, VP = vapor permeable and VI = vapor impermeable

[*] Density values, as determined by the lab using a modified ASTM D2395 method A approach

[**] No mean RH setpoints reported by manufacturers

[A.] ASTM Method A (dry cup)

[B.] ASTM Method B (wet cup)

Table 4. Fluid-applied Water-resistant Barriers (IP)

Material Density*	Water Vapor Permeance (measured): Mean RH Setpoint**	Water Vapor Permeance (measured): Perm	Water Vapor Permeance (manufacturer)**: Perm	Air Permeance: gpm/ft² at 75 bar, Measured	Air Permeance: gpm/ft² at 75 bar, Manufac-turer	Water Absorption Coefficient: lb/(ft²·s^0.5)	Sorption Isotherm: Mean RH Setpoint	Sorption Isotherm: % MC
Asphalt 56 lb/ft³	25%	0.1 (±0.01)	0.02	0.0003	0.003	8.2 * 10⁻⁵ (±2·10⁻⁵)	50%	0.4 (±0.03)
	75%	6 (±0.2)						
	90%	9 (±0.3)					90%	2.4 (±0.05)
	95%	36 (±3)						
Acrylic Polymer 78 lb/ft³	25%	0.3 (±0.01)	A. 0.03	0.0004	0.01	4.1 * 10⁻⁵ (±4·10⁻⁶)	50%	0.05 (±0.02)
	75%	2 (±0.03)						
	90%	3 (±0.07)					90%	1.2 (±0.08)
	95%	9 (±1)						
Latex VI 73 lb/ft³	25%	0.1 (±0.01)	A. <0.1	0.0003	PASS	6.1 * 10⁻⁷ (±4·10⁻⁶)	50%	0.01 (±0.02)
	75%	0.3 (±0.02)						
	90%	1 (±0.07)					90%	0.6 (±0.01)
	95%	1 (±0.2)						
Silicone 76 lb/ft³	25%	2 (±0.1)	10.5	0.0003	0.003	1.2 * 10⁻⁴ (±6·10⁻⁵)	50%	-1.2 (±0.2)
	75%	3 (±0.1)						
	90%	5 (±0.7)					90%	1.8 (±0.09)
	95%	5 (±0.1)						
STPE 81 lb/ft³	25%	3 (±0.03)	B. 18	0.0003	0.0009	4 * 10⁻⁴ (±4·10⁻⁴)	50%	0.6 (±0.1)
	75%	9 (±0.7)						
	90%	16 (±0.7)					90%	1.6 (±0.04)
	95%	24 (±0.3)						
Latex VP 87 lb/ft³	25%	0.3 (±0.05)	B. >10	0.0003	0.001	2 * 10⁻⁴ (±8·10⁻⁶)	50%	0.1 (±0.01)
	75%	21 (±0.4)						
	90%	52 (±2)					90%	0.8 (±0.1)
	95%	86 (±1)						

VP and VI describe the manufacturer's labelling for the products, VP = vapor permeable and VI = vapor impermeable

* Density values, as determined by the lab using a modified ASTM D2395 method A approach.

** No mean RH setpoints reported by manufacturers

A. ASTM Method A (dry cup)

B. ASTM Method B (wet cup)

All materials met the criteria for air barrier materials (< 0.02 Lps/m² @75 Pa; < 0.03 gpm/ft²). Interestingly, some test results suggested the WRB may have lower air permeance values than those reported by their manufactures. This finding included the silicone (0.0002 Lps/m² vs 0.003 Lps/m²; 0.0003 gpm/ft² vs 0.004 gpm/ft²), latex VP (0.0002 Lps/m² vs 0.001 Lps/m²; 0.0003 gpm/ft² vs 0.001 gpm/ft²), and acrylic polymer WRB (0.0003 Lps/m² vs 0.01 Lps/m²; 0.0004 gpm/ft² vs 0.01 gpm/ft²). These results may be due to the unqiue method of specimen preparation: for the air permeance test in RP-1696, all fluid-applied WRB were rolled onto glass-mat exterior sheathing. This approach was intended to reflect how WRB are applied in the field, while providing rigid backing for specimen mounting. The sheathing's air permeance had previously been determined for RP-1696: these materials are also air barriers, and values for them are reported in Table 6. A unique finding from the manufacturer data is the increase in reported air permeance for the asphalt-based WRB. The WRB product was applied to a concrete masonry unit, pointing to a potential interaction between the WRB and the substrate. Surfaces that are obviously highly-porous as well as rough surfaces may result in more pinholes and thus higher air permeance. Future work should consider reporting test results for WRB applied to typical substrate materials.

WRB materials are designed to be water-resistant, a key property for water control layers in building enclosures. However, the vapor permeability of WRBs vary. We sought to test a group of WRB products that reflected the vapor permeance properties of this group of materials. Test results were varied, and in general reflected the vapor permeance data reported by the manufacturers for a similar test condition. The test conditions included dry cup testing at 50% RH, and wet cup testing at 50%, 80%, and 90%. In some instances, test results diverged significantly from reported values. When comparing the test results for the dry cup method (i.e. mean RH setpoint of 25%) to the manufacturer's reported values for the vapor impermeable products (asphalt, acrylic polymer, and latex VI), all test results were higher than the reported values. These results maintained the materials' categorization as a vapor barrier (defined as having a permeance of less than 57 ng/Pa·s·m²; 1 Perm).

The test results for the three vapor permeable WRB (silicone, STPE, and latex VP) presented no consistent trends. Two of the materials, the STPE and the silicone WRB, had wet cup test (i.e. mean RH setpoint of 75%) vapor permeance results that were lower than the reported values for the silicone WRB. For example, the silicone WRB test result was 150 ng/Pa·s·m² (3 Perm), compared to the manufacturer reported value of 538 ng/Pa·s·m² (10.5 Perm). It is unclear if the latex VP material has a similar test result to the manufacturer reported results, due to the way the result is reported. An important insight from the test results is the effect of environmental conditions on vapor permeance performance. The asphalt-based product, at the highest mean RH setpoint of 95%, had a vapor permeance value above the vapor permeable cutoff of 570 ng/Pa·s·m² (10 Perm). As well, it is likely that the method of specimen preparation is impacting the test results, as all test specimens were the WRB applied to a glass-mat sheathing. No details are provided for the specimen preparation in the manufacturer specification sheets, precluding comparison.

All of the materials have a low rate of water absorption. Generally, the absorption values mirror the vapor permeance data: the more vapor open a material was, the more it absorbed moisture. No patterns emerged from the sorption isotherm data, with the exception that higher RH setpoints elicited the adsorption of more moisture for all products. The negative value for the silicone WRB is possibly an anomaly, or may be reflecting a loss related to subtle and ongoing material curing. Manufacturers do not currently report these values, and we were unable to locate water absorption coefficient or sorption isotherm data for these materials in the open literature.

Insulation Materials

Aerogel insulation is a unique insulation product. Initially developed by the aerospace industry, aerogel is used in a range of industries, from aerospace to construction to textiles and clothing. It maintains its insulative abilities at extreme temperature conditions and is resistant to water. Aerogel blanket insulation used in construction applications is thin compared to other insulating batts, boards, and blankets (5 to 10 mm; 0.2 to 0.4 inches). It has a reported R-value of 10 per inch (R_{SI} 1.8 per 25.4 mm) (Baetens, Jelle, and Gustavsen 2011). Manufacturers report a thermal conductivity of 0.014 W/m·K for 5 mm thick blankets (0.1 Btu·in/h·ft²·°F at 0.2 inches). Slightly higher thermal conductivity values are reported in the literature, ranging from 0.018 W/m·K to 0.023 W/m·K (0.12 Btu·in/h·ft²·°F to 0.16 Btu·in/h·ft²·°F) (Lakatos 2017b; 2017a; Bardy, Mollendorf, and Pendergast 2007; Hoseini and Bahrami 2017; Nosrati and Berardi 2018). Research providing information on other hygrothermal characteristics of aerogel blankets is also available (Hoseini and Bahrami 2017; Lakatos 2017b; Nosrati and Berardi 2018). Results are summarized in Table 5, which includes research results where the materials tested matched those included in RP-1696.

The thermal conductivity test results are in agreement with the manufacturer's reported values: the measured results are 0.001 W/m·K (0.007 Btu·in/h·ft²·°F) lower than those reported by the manufacturer. The standard aerogel is less conductive than the fire-rated aerogel, by 0.003 W/m·K (0.02 Btu·in/h·ft²·°F) at all test temperatures. These values were consistent with the literature as well (Table 5).

All reported water vapor permeance values confirm the material is highly permeable, with values ranging from 2005 ng/Pa·s·m² (35 Perm) (test results), to 2408 ng/Pa·s·m² (42 Perm) (Nosrati and Berardi 2018), up to 3936 ng/Pa·s·m² (69 Perm) reported by the manufacturer. The manufacturer's data indicate the material is more permeable than what was measured by the lab, nearly double some of the measured values. However, all results indicate this material is highly permeable. Water absorption data reported by Lakatos (2017b) are several orders of magnitude higher than RP-1696 test results (6.0×10^{-2} $kg/m^2 \cdot s^{0.5}$ vs 2.7×10^{-8} $kg/m^2 \cdot s^{0.5}$). The materials tested may be different: the aerogel manufacturer is not documented in Lakatos (2017b). Sorption isotherm data was available (Nosrati and Berardi 2018), and is an order of magnitude higher than the test results. Although both materials are the same and test methods were similar, these differences are significant. The cause of these differences remains unclear. No major differences are noted between manufacturer data and the standard aerogel test results. The fire-rated aerogel, although there was no comparative data for sorption isotherm results, demonstrated a stronger resistance to water adsorption than its standard counterpart. This may be due to the fire-proofing compounds in the material, inhibiting water adsorption.

Table 5. Aerogel Insulation Material Properties (SI)

Aerogel (standard)
164 kg/m³*
10 mm**

Source	Thermal Conductivity		Water Vapor Permeance		Water Absorption Coefficient	Sorption Isotherm	
	Mean Temperature Setpoint	$W/m^2 \cdot K$	Mean RH Setpoint	ng/ $Pa \cdot s \cdot m^2$	$kg/m^2 \cdot s^{0.5}$	Mean RH Setpoint	% MC
Manufacturer	N/A	0.015	N/A	3936***	N/A	N/A	
Lakatos 2017b	N/A		N/A		6.0×10^{-2}	N/A	
Bardy et al 2007		0.018	N/A		N/A	N/A	
Nosrati & Berardi 2018		0.018	N/A	A. 2408	N/A	50%	13
						70%	13
						95%	17
RP-1696	10ºC	0.014 ($\pm 7.6 \cdot 10^{-5}$)	25%	2005 (±43)	2.7×10^{-8} ($\pm 2.8 \cdot 10^{-9}$)	50%	2.5 (±0.3)
	24ºC	0.015 ($\pm 7.9 \cdot 10^{-5}$)	75%	2234 (±44)		80%	3.6 (±0.5)
						90%	4.1 (±0.5)

Fire-rated aerogel
234 kg/m³*
10 mm**

	Thermal Conductivity		Water Vapor Permeance		Water Absorption Coefficient	Sorption Isotherm	
	Mean Temperature Setpoint	$W/m^2 \cdot K$	Mean RH Setpoint	ng/ $Pa \cdot s \cdot m^2$	$kg/m^2 \cdot s^{0.5}$	Mean RH Setpoint	% MC
Manufacturer	N/A	0.018	N/A		N/A	N/A	
RP-1696	10ºC	0.017 ($\pm 1.9 \cdot 10^{-4}$)	25%	2234 (±35)	2.5×10^{-8} ($\pm 6.4 \cdot 10^{-9}$)	50%	1.8 (±0.5)
	24ºC	0.018 ($\pm 1.9 \cdot 10^{-4}$)	75%	2798 (±12)		80%	1.6 (±0.2)
						90%	2 (±0.5)

* Density values, as determined by the lab using a modified ASTM D2395 method A approach.
** Reported thickness
*** Converted to permeance from water vapor diffusion resistance factor value ($\mu = 4.7$)
A. ASTM E96 Wet cup

Table 5. Aerogel Insulation Material Properties (IP)

Aerogel (standard)
10.25 lb/ft³*
0.4 inches**

Source	Thermal Conductivity		Water Vapor Permeance		Water Absorption Coefficient	Sorption Isotherm	
	Mean Temp-erature Setpoint	Btu·in/ h·ft²·°F	Mean RH Setpoint	Perm	lb/ft²·s^0.5	Mean RH Setpoint	% MC
Manufacturer	N/A	0.104	N/A	69***	N/A	N/A	
Lakatos 2017	N/A		N/A		1.2 * 10⁻²	N/A	
Bardy et al 2007		0.125	N/A		N/A	N/A	
Nosrati & Berardi 2018		0.125	N/A	A. 42	N/A	50% 70% 95%	13 13 17
RP-1696	50ºF 75ºF	0.097 (±1.33·10⁻⁵) 0.104 (±1.39·10⁻⁵)	25% 75%	35 (±1) 39 (±1)	5.5 * 10⁻⁹ (±5.7·10⁻¹⁰)	50% 80% 90%	2.6 (±0.3) 3.8 (±0.5) 4.2 (±0.5)

Fire-rated aerogel
15 lb/ft³*
0.4 inches**

	Thermal Conductivity		Water Vapor Permeance		Water Absorption Coefficient	Sorption Isotherm	
	Mean Temp-erature Setpoint	Btu·in/ h·ft²·°F	Mean RH Setpoint	Perm	lb/ft²·s^0.5	Mean RH Setpoint	% MC
Manufacturer	N/A	0.125	N/A		N/A	N/A	
RP-1696	50ºF 75ºF	0.118 (±3.3·10⁻⁵) 0.125 (±3.3·10⁻⁵)	25% 75%	39 (±1) 49 (±0.2)	5.1 * 10⁻⁹ (±1.3·10⁻⁹)	50% 80% 90%	1.8 (±0.5) 1.6 (±0.2) 2 (±0.5)

* Density values, as determined by the lab using a modified ASTM D2395 method A approach.
** Reported thickness
*** Converted to permeance from water vapor diffusion resistance factor value ($\mu = 4.7$)
A. ASTM E96 Wet cup

Glass-Mat Exterior Gypsum Sheathing Materials

Glass-mat exterior gypsum sheathing is a product designed for exterior non-combustible sheathing applications. Generally, it is "manufactured with a wax-treated, water-resistant core faced with water-repellent paper on both face and back surfaces and long edges." (American Gypsum 2019). There are several manufacturers in North America. There is no prior data for these materials in previous editions of the HOF. RP-905 recommended this material be included in future HOF updates, due to its increasing popularity (McGowan 2007). The RP-1696 testing scheme involved products from three manufacturers, including type x and fire-resistant products.

We were unable to locate comparative data from within the literature. In part, this is due to the significant focus in the literature on testing glass-mat sheathing's behavior when installed in a complete wall assembly. However, the manufacturers do provide detailed data specification sheets. The manufacturer data, along with test data, is supplied in Table 6. To maintain brevity, test results are provided only for the type x products.

All products met the air barrier criterion (< 0.02 Lps/m^2 at 75 Pa; < 0.03 gpm/ft^2 at 75 bar), based on the RP-1696 test results. The vapor permeance data for all three products are in agreement. All test data characterize the materials as being two to three times more vapor open than the reported data. Thermal resistance results have similar trends to the vapor permeance results: test values measured two to three times higher than those reported by the manufacturer. This may be an artefact of the variability in construction materials, though it is a consistent pattern across all three products. However, a more probable explanation is that factors related to the manufacturing and proprietary composition are affecting the test results, as well as subtle variations in factors relating to test methods. Although we did apply the same test standards as the manufacturer, to determine both vapor permeance and thermal conductivity (ASTM 2016, 2015, respectively), specific details about the testing methodologies were not acquired from the manufacturers. This precludes further discussion about test factors affecting results.

The water adsorption properties for these products were generally similar for the 30% and 50% RH setpoint, and then the moisture content for material 3 at the 80% RH setpoint were more than 3 times that of the other two products (16.9% and 13.3% vs 59.7%). Interestingly, material 3's measured vapor permeance is the lowest in the group of products (2077 ng/Pa·s·m^2 vs 3039 and 3075 ng/Pa·s·m^2) (36 Perm vs 53 and 54 Perm), while the manufacturer reported vapor permeance values are the highest. The test results may be explained by material 3's density, as it was the densest product. Another finding worth noting is the difference in water absorption coefficients between the products. Material 2 has a rate of water absorption 2 orders of magnitude higher than material 1 and 3.

Table 6. Glass-Mat Gypsum Substrate (Type X) Material Properties (SI)

Source	Thermal Conductivity		Water Vapor Permeance		Air Permeance	Water Absorption Coefficient	Sorption Isotherm	
Material 1 693 kg/m^3* 16 mm**								
	Mean Temp-erature Setpoint	**m^2·K/W**	**Mean RH Setpoint**	**ng/ Pa·s·m^2**	**Lps/m^2 at 75 Pa**	**kg/m^2·s$^{0.5}$**	**Mean RH Setpoint**	**% MC**
Manufacturer		0.118	N/A	970	N/A	N/A	N/A	
RP-1696	10°C 24°C	0.312 0.311	25% 75%	3039 (±26) 3448 (±85)	0.005 (±4·10^{-6})	0.008 (±2·10^{-3})	30% 50% 80%	3.3 (±0.3) 8.3 (±0.3) 16.9 (±1.4)
Material 2 650 kg/m^3* 16 mm**								
Manufacturer		0.100	N/A	1200	N/A	N/A	N/A	
RP-1696 10°C 24°C	10°C 24°C	0.293 0.294	25% 75%	3075 (±75) 3452 (±159)	0.007 (±4·10^{-6})	0.263 (±4·10^{-3})	30% 50% 80%	2.5 (±0.2) 7.2 (±0.2) 13.3 (±0.3)
Material 3 737 kg/m^3* 16 mm**								

Source	Mean Temperature Setpoint	Thermal Conductivity	Mean RH Setpoint	Perm	Air Permeance	Water Absorption Coefficient	Mean RH Setpoint	% MC
Manufacturer		0.088	N/A	1602	N/A	N/A	N/A	
RP-1696 10ºC 24ºC	10ºC 24ºC	0.301 0.298	25% 75%	2077 (±120) 2772 (±74)	0.007 (±4·10-6)	0.003 (±4·10-4)	30% 50% 80%	3.4 (±0.1) 7.9 (±0.3) 59.7 (±1.6)

* Density values, as determined by the lab using a modified ASTM D2395 method A approach.
** Reported thickness

Table 6. Glass-Mat Gypsum Substrate (Type X) Material Properties (IP)

Source	Thermal Conductivity		Water Vapor Permeance		Air Permeance	Water Absorption Coefficient	Sorption Isotherm	
	Mean Temperature Setpoint	ft²·h·°F/Btu	Mean RH Setpoint	Perm	gpm/ft² at 75 bar	lb/ft²·s0.5	Mean RH Setpoint	% MC
Material 1, 43 lb/ft³*, 0.63 inches								
Manufacturer		0.67	N/A	17	N/A	N/A	N/A	
RP-1696	50ºF 75.2ºF	1.77 1.77	25% 75%	53 (±0.5) 60 (±1.5)	0.007 (±6·10-6)	0.002 (±5·10-4)	30% 50% 80%	3.3 (±0.3) 8.3 (±0.3) 16.9 (±1.4)
Material 2, 41 lb/ft³*, 0.63 inches								
Manufacturer		0.57	N/A	21	N/A	N/A	N/A	
RP-1696	50ºF 75.2ºF	1.66 1.67	25% 75%	54 (±1.3) 60 (±2.8)	0.01 (±6·10-6)	0.05 (±9·10-4)	30% 50% 80%	2.5 (±0.2) 7.2 (±0.2) 13.3 (±0.3)
Material 3, 46 lb/ft³*, 0.63 inches								
Manufacturer		0.5	N/A	28	N/A	N/A	N/A	
RP-1696	50ºF 75.2ºF	1.71 1.69	25% 75%	36 (±2.1) 49 (±0.1)	0.01 (±6·10-6)	0.0006 (±8·10-5)	30% 50% 80%	3.3 (±0.3) 8.3 (±0.3) 16.9 (±1.4)

* Density values, as determined by the lab using a modified ASTM D2395 method A approach.
** Reported thickness

CONCLUSION

The focus of the RP-1696 project was to present ASHRAE with an updated dataset for new and modified building materials. This summary highlights some of the more interesting results, contextualizing them within the existing literature and available data. This is a small portion of the test results. Interestingly, the wood-based materials have maintained their thermal transmission properties while their response to moisture has changed. Some new materials, such as aerogel, have been researched extensively and valuable material data already exists within the literature. Given the focus on energy consumption and building energy-efficient buildings, this is not unexpected. The lack of data on materials such as glass-mat exterior sheathing and fluid-applied WRBs indicates the need for more research on these materials. Comprehensive and detailed hygrothermal data will result in more accurate and realistic models and designs.

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