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Variations in the hygrothermal properties of several wood-based building products

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ABSTRACT: A systematic investigation of the hygrothermal properties of a number of oriented strand boards, plywood products, wood fibreboards and composite wood sidings has resulted in new information on the variations of thermal conductivity, water vapour permeability, moisture diffusivity, sorption- desorption-suction isotherms, water absorption coefficient and air permeability of these classes of products in North America. The experimental and analytical procedures used in the investigation are all based either on International Standards or on well-documented and peer-reviewed approaches.
This paper presents the description of the products in each category and detailed information on the range of properties. The details include, density and temperature dependences of thermal conductivity, dependence of vapour resistance factor on relative humidity, dependence of moisture diffusivity on moisture concentration, equilibrium moisture content for the full range of relative humidity, variations in the water absorption coefficients and dependence of air permeability on pressure difference.

1 INRODUCTION

With the advent of high power personal computers, hygrothermal computer models have become powerful tools for building physicists and building practitioners alike. Researchers active in the field of hygrothermal analyses have developed many such models in recent years (Hens, 1996; Trechsel, 2001). All these models require a set of very reliable inputs to yield meaningful results. Among these inputs include the properties of the building materials. The most commonly used properties today are those from an International Energy Agency Annex (Kumaran, 1996). As building materials evolve there is a need for continuous updating of the information on their hygrothermal properties. At the Institute for Research in Construction two recently concluded projects have generated detailed information on the hygrothermal properties of more than 70 building products that are currently used in Canada and the United States of America (Kumaran et al. 2002a, Kumaran et al. 2002b). One of these projects (Kumaran et al. 2002a) was specifically looking at the ranges of the properties shown by contemporary products in North America. The products chosen included wood and wood based materials, bricks, mortar, stucco and building membranes. This paper reports only the information on wood-based products such as oriented strand board (OSB), plywood, wood fibreboard and wood siding.

The properties that have been measured in both projects include:

thermal conductivity
equilibrium moisture content
water vapour permeance
water absorption coefficient
moisture diffusivity and
air permeance

Thermal conductivity was determined in accordance with the ASTM Standard C518 (ASTM Book of Standards 2001). Sorption-desorption measurements followed the ASTM Standard 1498 (ASTM Book of Standards 2001). Pressure plate measurements (Hansen, 1998) were used to define suction. Water vapour permeance was measured using an extension of ASTM Standard E96 (ASTM Book of Standards 2001; Lackey et al., 1995; Kumaran, 2000). Water absorption coefficient was determined as described in CEN Draft Standard 89 N 370 E. Gamma-ray method for measuring transient moisture distribution (Kumaran & Bomberg, 1985) and Boltzmann transformation method (Bruce & Klute, 1956) were used to derive moisture diffusivity (Kumaran et al, 1989; Marchand & Kumaran, 1994). Air permeance was measured using a method developed at the Institute for Research in Construction (Bomberg & Kumaran, 1986).

2 MATERIALS

All materials that were used in the investigations are commercial products that are readily available in North America and are commonly used in current constructions. General descriptions of the products are given below.

2.1 *OSB*

Six different OSB products were investigated. The bulk densities of these products varied from 575 kg m^{-3} to 725 kg m^{-3}. The strands included various wood species such as aspen, poplar, birch and southern yellow pine. The thickness ranged between 10 mm and 11.5 mm. All products are available as 1.2 m x 2.4 m boards.

2.2 *Plywood*

Six different plywood products were investigated. The bulk densities of the products varied from 400 kg m^{-3} to 600 kg m^{-3}. The products were certified as conforming to Canadian plywood manufacturing standards CSA O151 Canadian Softwood Plywood (CSP) or CSA O121 Douglas Fir Plywood (DFP). These standards permit a variety of wood species to be used in veneer plies, except that Douglas Fir is required for the outer plies of CSA O121 DFP. The thickness of the products varied from 9.5 mm to 13 mm. All products are available as 1.2 m x 2.4 m boards.

2.3 *Wood fibreboard*

Eight different fibreboard products were investigated. Two products were natural fibreboards (no coating or facer) and four were coated with a thin (fraction of a millimeter) layer of a black material on both major surfaces. One other product had a paper facer on one major surface and the last one had an aluminium foil facer on one major surface. The bulk densities of the products varied from 235 kg m^{-3} to 330 kg m^{-3} and the thickness from 11 mm to 13 mm. All products are available as 1.2 m x 2.4 m boards.

2.4 *Composite wood siding*

Five different panels were investigated. The substrates of three of the products were compressed fibreboard, the fourth OSB and the fifth plywood. All had vinyl coatings on one major surface. The bulk densities of the products varied from 580 kg m^{-3} to 930 kg m^{-3} and the thickness from 10.5 mm to 15.1 mm. All products are available as 1.2 m x 2.4 m panels.

3 HYGROTHERMAL PROPERTIES OF OSB

3.1 *Thermal conductivity*

Thermal conductivity, λ of the OSB products at a mean temperature of 24°C increases linearly with density, ρ as:

$$\lambda = a + b\rho \qquad (1)$$

with

$a = -0.0339$ W m^{-1} K^{-1} and

$b = 2.05 \times 10^{-4}$ (W m^{-1} K^{-1}) / (kg m^{-3})

For the mean temperature range from 0°C to 24°C, the temperature coefficient of thermal conductivity of all products is approximately 2×10^{-4} W m^{-1} K^{-2}.

3.2 *Equilibrium moisture content*

The equilibrium moisture content of each product was determined from sorption, desorption and suction measurements and the results are separately reported below.

Table 1. Results from sorption measurements on the OSB products.

Relative humidity	Moisture content
%	kg kg^{-1}
50	0.050 ± 0.017
69.3	0.086 ± 0.012
91.5	0.163 ± 0.008

Table 2. Results from desorption measurements on the OSB products.

Relative humidity	Moisture content
%	kg kg^{-1}
48	0.051 ± 0.003
69	0.105 ± 0.007
88.9	0.142 ± 0.005
93	0.205 ± 0.030

Table 3. Results from suction measurements on the OSB products.

Suction	Moisture content
Pa	kg kg^{-1}
1×10^6	0.58 ± 0.09
3×10^5	0.71 ± 0.10
1×10^5	0.88 ± 0.12
3×10^4	1.06 ± 0.11
1×10^4	1.11 ± 0.12
4×10^3	1.15 ± 0.11
0	1.50 ± 0.14

3.3 *Vapour resistance factor*

Water vapour permeances of all products were measured at various relative humidity differences. The highest and the lowest of these values are reported below in terms of the vapour resistance factors to define the range.

Table 4. Vapour resistance factors of OSB products.

Relative humidity	Vapour resistance factor	
	Highest	Lowest
%	dimensionless	
20	1114	956
30	495	423
40	279	238
50	177	152
60	123	105
70	89.5	76.6
80	68.1	58.2
90	53.6	45.8
100	43.0	36.8

3.4 *Water absorption coefficient*

The water absorption coefficients of the OSB products, measured across the major surfaces varied from 0.0011 kg m^{-2} $s^{-½}$ to 0.0033 kg m^{-2} $s^{-½}$.

3.5 *Moisture diffusivity*

Moisture diffusivities of the OSB products, as determined from a water absorption process through the edges (Marchand & Kumaran, 1994) gave the lower and upper values listed below.

Table 5. Moisture diffusivities of OSB products.

Moisture content	Moisture diffusivity	
	Lowest	Highest
kg m^{-3}	m^2 s^{-1}	
50	1.70E-09	2.00E-09
70	1.21E-09	1.33E-09
100	8.45E-10	9.12E-10
150	5.83E-10	6.31E-10
200	4.67E-10	5.03E-10
250	4.04E-10	4.31E-10
300	3.64E-10	3.86E-10
350	3.36E-10	3.56E-10
400	3.14E-10	3.36E-10
450	2.98E-10	3.22E-10
500	2.84E-10	3.12E-10
525	2.78E-10	3.07E-10
550	2.73E-10	3.04E-10
575	2.68E-10	3.00E-10
600	2.64E-10	2.97E-10

3.6 *Air permeance*

The air permeances of the OSB products are independent of the pressure differences in a range between 25 Pa and 600 Pa. The values for the different products ranged between 3.7E-09 kg m^{-2} Pa^{-1} s^{-1} and 3.0E-07 kg m^{-2} Pa^{-1} s^{-1}.

4 HYGROTHERMAL PROPERTIES OF PLYWOOD

4.1 *Thermal conductivity*

Thermal conductivity, λ of the plywood products at a mean temperature of 24°C increases linearly with density, ρ as in equation (1),
with
a = 0.010 W m^{-1} K^{-1} and
b = 1.67 x 10^{-4} (W m^{-1} K^{-1}) / (kg m^{-3})
For the mean temperature range from 0°C to 24°C, the temperature coefficient of thermal conductivity of all products is approximately 2 x 10^{-4} W m^{-1} K^{-2}.

4.2 *Equilibrium moisture content*

The equilibrium moisture content of each product was determined from sorption, desorption and suction measurements and the results are separately reported below.

Table 6. Results from sorption measurements on the plywood products.

Relative humidity	Moisture content
%	kg kg^{-1}
49.9	0.060 ± 0.015
69	0.095 ± 0.006
90	0.160 ± 0.006

Table 7. Results from desorption measurements on the plywood products.

Relative humidity	Moisture content
%	kg kg^{-1}
48	0.062 ± 0.003
70	0.108 ± 0.008
91	0.187 ± 0.010

Table 8. Results from suction measurements on the plywood products.

Suction	Moisture content
Pa	kg kg^{-1}
1×10^6	0.59 ± 0.21
3×10^5	0.82 ± 0.17
1×10^5	0.94 ± 0.22
3×10^4	1.23 ± 0.11
0	1.60 ± 0.37

4.3 *Vapour resistance factor*

Water vapour permeances of all products were measured at various relative humidity differences. The highest and the lowest of these values are reported below in terms of the vapour resistance factors to define the range.

Table 9. Vapour resistance factors of plywood products.

Relative humidity	Vapour resistance factor	
	Highest	Lowest
%	dimensionless	
20	465	361
30	281	218
40	203	157
50	142	111
60	89.6	69.8
70	51.0	39.6
80	28.0	21.7
90	15.3	11.9
100	8.5	6.6

4.4 *Water absorption coefficient*

The water absorption coefficients of the plywood products, measured across the major surfaces varied from 0.0013 kg m^{-2} s$^{-½}$ to 0.0039 kg m^{-2} s$^{-½}$.

4.5 *Moisture diffusivity*

Moisture diffusivities of the plywood products, as determined from a water absorption process through the edges (Marchand & Kumaran, 1994) gave the lower and upper values listed below.

Table 10. Moisture diffusivities of plywood products.

Moisture content	Moisture diffusivity	
	Lowest	Highest
kg m^{-3}	m^2 s^{-1}	
50	8.45E-09	9.52E-09
60	6.34E-09	6.99E-09
80	3.82E-09	4.06E-09
100	3.45E-09	3.79E-09
110	3.79E-09	4.14E-09
120	4.31E-09	4.67E-09
130	4.89E-09	5.28E-09
140	5.43E-09	5.84E-09
150	5.85E-09	6.29E-09
160	6.10E-09	6.58E-09
170	6.15E-09	6.66E-09
180	6.04E-09	6.56E-09
200	5.39E-09	5.87E-09
220	4.45E-09	4.88E-09
240	3.55E-09	3.92E-09
280	2.43E-09	2.69E-09
320	1.78E-09	1.98E-09
360	1.20E-09	1.37E-09
400	8.70E-10	1.01E-09

4.6 *Air permeance*

The air permeances of the plywood products are independent of the pressure differences in a range between 600 Pa and 5 kPa. The values for the different products ranged between 2.1E-09 kg m^{-2} Pa^{-1} s^{-1} and 1.6E-07 kg m^{-2} Pa^{-1} s^{-1}.

5 HYGROTHERMAL PROPERTIES OF FIBREBOARD

5.1 *Thermal conductivity*

Thermal conductivity, λ of the fibreboard products at a mean temperature of 24°C increases linearly with density, ρ as in equation (1),
with
$a = 0.0260$ W m^{-1} K^{-1} and
$b = 8.4 \times 10^{-5}$ (W m^{-1} K^{-1}) / (kg m^{-3})
For the mean temperature range from 0°C to 24°C, the temperature coefficient of thermal conductivity of all products is 1.2×10^{-4} W m^{-1} K^{-2}.

5.2 *Equilibrium moisture content*

The equilibrium moisture contents of six out of the eight products are separately reported below for each product, as obtained from the sorption and desorption measurements. Pressure plate measurements were inconclusive and values are given only for one set of measurements for comparison.

Table 11. Equilibrium moisture contents of six fibreboard products from sorption measurements.

RH, %	Moisture content, kg kg^{-1}					
	Natural1	Natural2	Black1	Black2	Black3	Black4
50	0.029	0.082	0.075	0.077	0.046	0.051
69	0.061	0.109	0.101	0.104	0.072	0.079
91	0.160	0.193	0.174	0.183	0.137	0.146

Table 12. Equilibrium moisture contents of six fibreboard products from desorption measurements.

RH, %	Moisture content, kg kg^{-1}					
	Natural1	Natural2	Black1	Black2	Black3	Black4
50	0.049	0.057	0.052	0.052	0.041	0.044
69.5	0.090	0.096	0.086	0.087	0.071	0.076
91	0.187	0.183	0.164	0.163	0.146	0.147

The saturation moisture contents (kg kg^{-1}) that correspond to zero suction were 3.9 and 4.4 for the two natural boards and 4.4, 3.7, 3.0, and 3.1 for the black-coated boards. For a suction of 3 x 10^5 Pa the measured values (kg kg^{-1}) were 0.30 and 0.41 for the natural boards and 0.44, 0.43, 0.56 and 0.47 for the black-coated boards. Equilibrium attainment was very slow at all pressure conditions and further measurements were not pursued.

5.3 *Vapour resistance factor*

Water vapour permeances of all products were measured at various relative humidity differences. The product with the aluminium facer showed a vapour resistance factor as high as 10000 for the full range of relative humidity (rh). The vapour resistance factor of the product with the paper facer varies linearly with relative humidity from 135 at 20 % rh to 52 as 100 % rh is approached. All other products show linear dependence of vapour resistance factor on rh as well, but within a narrow range. For the two natural fibreboards it varies from 6.1 to 4.8 for one and 5.2 to 4.6 for the other as rh changes from 20 % to 100 %. For the black-coated boards the corresponding values are marginally higher and varies from 11.2 to 7.4.

5.4 *Water absorption coefficient*

The water absorption coefficients (kg m^{-2} $s^{-½}$) of the fibreboard products, measured across the major surfaces vary as follows. For the two natural fibreboards the values are 0.0021 and 0.0052 respectively. For the four black-coated products the water absorption coefficient varied only from 0.0010 to 0.0015 while that for the product with the paper facer is 0.0019. The absorption coefficient for the surface with the aluminium foil is as low as 0.0004.

5.5 *Moisture diffusivity*

Moisture diffusivities of six fibreboard products, as determined from a water absorption process through the edges (Marchand & Kumaran, 1994) gave the values listed below. The remaining two boards did not yield any analysable results. Even for those that gave analysable results, the range of moisture concentration developed during the moisture pick-up process was far short of saturation moisture contents.

Table 13. Moisture diffusivities of fibreboard products.

Moisture content	Moisture diffusivity		
	Natural1	Natural2	PF*
kg m^{-3}	m^2 s^{-1}		
50	3.20E-10	2.54E-09	1.44E-09
60	2.53E-10	1.77E-09	1.41E-09
80	1.95E-10	1.11E-09	2.46E-09
100	1.70E-10	8.22E-10	2.32E-09
110	1.63E-10	7.28E-10	1.33E-09
120	1.57E-10	6.55E-10	8.91E-10
130	1.53E-10	5.96E-10	6.42E-10
140	1.50E-10	5.46E-10	4.78E-10
150	1.48E-10	5.05E-10	3.58E-10
160	1.46E-10	4.70E-10	
180	1.44E-10	4.13E-10	
200	1.44E-10	3.69E-10	
220	1.45E-10	3.34E-10	
240	1.47E-10	3.05E-10	
280	1.54E-10	2.60E-10	
320	1.65E-10	2.27E-10	
360	1.79E-10	2.02E-10	
400	1.98E-10	1.82E-10	
440	2.22E-10		
480	2.55E-10		
520	2.98E-10		
560	3.53E-10		
580	3.86E-10		

* PF stands for the product with the paper facer

5.6 *Air permeance*

The air permeances of the fibreboard products without any facers are independent of the pressure differences in a range between 10 Pa and 70 Pa. The values for the different products ranged between 1.7E-05 kg m^{-2} Pa^{-1} s^{-1} and 3.1E-05 kg m^{-2} Pa^{-1} s^{-1}.

The product with the paper facer has much lower air permeance and for pressure differences up to 500 Pa it is independent of the difference. The measured value is 1.9E-07 kg m^{-2} Pa^{-1} s^{-1}. The product with the aluminium facer is impermeable to air.

Table 14. Moisture diffusivities of fibreboard products, continued.

Moisture content	Moisture diffusivity		
	Black1	Black2	Black3
kg m^{-3}	m^2 s^{-1}		
30	9.76E-09	3.03E-08	4.56E-08
40	5.71E-09	1.86E-08	9.94E-09
50	2.29E-09	1.18E-08	5.38E-09
60	1.26E-09	7.88E-09	3.55E-09
70	7.55E-10	5.48E-09	2.57E-09
80	4.90E-10	3.96E-09	1.96E-09
90	3.40E-10	2.95E-09	1.94E-09
100		2.25E-09	1.24E-09
110		1.40E-09	
120		1.13E-09	
130		9.31E-10	
140		7.63E-10	
150		6.26E-10	

6 HYGROTHERMAL PROPERTIES OF COPMOSITE WOOD SIDING

6.1 *Thermal conductivity*

Thermal conductivity of the composite wood siding products does not show any dependency on the bulk density, for the five products that have been investigated here. At a mean temperature of 24°C, for all products the thermal conductivity is approximately 0.1 W m^{-1} K^{-1}. For the mean temperature range from 0°C to 24°C, the temperature coefficient of thermal conductivity of all siding products is approximately 4 x 10^{-4} W m^{-1} K^{-2}.

6.2 *Equilibrium moisture content*

The equilibrium moisture contents of the five products are separately reported below for each product, as obtained from the sorption and desorption measurements. Pressure plate measurements were inconclusive and values are given only for one set of measurements for comparison.

Table 15. Equilibrium moisture contents of five composite wood siding products from sorption measurements.

RH, %	Moisture content, kg kg^{-1}				
	Siding 1	Siding 2	Siding 3	Siding 4	Siding 5
50	0.048	0.051	0.048	0.051	0.046
70	0.079	0.081	0.071	0.072	0.069
91	0.157	0.163	0.131	0.120	0.131

Table 16. Equilibrium moisture contents of five composite wood siding products from desorption measurements.

RH, %	Moisture content, kg kg^{-1}				
	Siding 1	Siding 2	Siding 3	Siding 4	Siding 5
50	0.059	0.058	0.056	0.058	0.043
69	0.098	0.098	0.091	0.092	0.076
91	0.178	0.173	0.160	0.154	0.134

The saturation moisture contents (kg kg^{-1}) that correspond to zero suction for the five products were respectively 1.1, 1.1, 0.85, 0.66 and 0.91. For a suction of 3 x 10^5 Pa the measured values (kg kg^{-1}) were respectively 0.65, 0.63, 0.38, 0.37 and 0.38. Equilibrium attainment was very slow at all pressure conditions and further measurements were not pursued.

6.3 *Vapour resistance factor*

Water vapour permeances of all products were measured at various relative humidity differences. These are reported below as vapour resistance factors for each product.

Table 17. Vapour resistance factors of five composite wood siding products.

RH, %	Vapour resistance factor, dimensionless				
	Siding 1	Siding 2	Siding 3	Siding 4	Siding 5
20	1828	3080	78.2	387	48.2
30	916	1048	67.2	211	46.0
40	562	488	57.9	138	44.0
50	384	270	49.7	98.2	42.1
60	280	166	42.8	74.6	40.4
70	216	110	36.7	58.8	38.6
80	171	76.5	31.5	47.9	36.9
90	140	55.8	26.9	40.0	35.3
100	117	41.8	23.0	33.9	33.7

6.4 *Water absorption coefficient*

The water absorption coefficients (kg m^{-2} $s^{-½}$) of the siding products, measured across the major surfaces with the coating vary between 0.0004 kg m^{-2} $s^{-½}$ and 0.0006 kg m^{-2} $s^{-½}$.

6.5 *Moisture diffusivity*

Moisture diffusivities of three siding products, as determined from a water absorption process through the edges (Marchand & Kumaran, 1994) gave the values listed below. The remaining two products did not yield any analysable results. Also for one that yielded analysable results, the range of moisture concentration developed during the moisture pick-up process was far short of saturation moisture content.

Table 13. Moisture diffusivities of composite wood siding products.

Moisture content	Moisture diffusivity		
	Siding 2	Siding 4	Siding 5
kg m^{-3}	m^2 s^{-1}		
50	4.69E-09	4.32E-10	6.20E-11
60	2.84E-09	3.02E-10	5.53E-11
80	1.66E-09	1.88E-10	4.83E-11
100	1.61E-09	1.36E-10	4.47E-11
110	1.63E-09	1.19E-10	4.36E-11
120	1.60E-09	1.06E-10	4.26E-11
130	1.52E-09	9.56E-11	4.18E-11
140	1.42E-09		4.12E-11
150	1.30E-09		4.07E-11
160	1.19E-09		4.03E-11
180	1.03E-09		3.96E.11
200	1.01E-09		3.91E-11
220	1.08E-09		3.88E-11
240	1.16E-09		3.87E-11
280	1.13E-09		3.87E-11
320	8.62E-10		3.92E-11
360	6.34E-10		3.98E-11
400	4.71E-10		4.12E-11
440	2.08E-10		4.33E-11
470	1.52E-10		4.57E-11
500			4.95E-11

6.6 *Air permeance*

The air permeances (kg m^{-2} Pa^{-1} s^{-1}) of the five siding products were respectively 1.8E-08, zero (impermeable), 1.8E-08, 2.4E-09 and 4.3E-07. These are independent of pressure differences up to 1000 Pa.

7 CONCLUDING REMARKS

Out of the four types of wood based products whose hygrothermal properties are listed above, only for OSB and plywood is it possible to define the properties within a range. For these two materials an upper and lower limit can be identified, as shown in Tables 1 to 10. More detailed investigations at the institute that include information from measurements on 11 products in each category have further confirmed this. For the other two products no such definition of ranges is possible. One has to know the product details. For example, for the wood fibreboard the moisture transport and storage properties may differ widely for different details - whether it is natural fibreboard or it has coating or facers.

An earlier investigation at the Institute for Research in Construction (Wang & Kumaran) attempted to answer the question: How well does one have to know the hygrothermal properties? Hygrothermal model calculations were performed with reference to a well-controlled drying experiment on a type of a cement board. The conclusions made were the following. To make a significant change in the details of the drying curve, the vapour resistance factor must be more than 20 % displaced from the right value and the moisture diffusivity must differ by as much as 50 %. However, the equilibrium moisture content should be known within 5 % for acceptable agreement between the experimental drying curve and simulated drying curve.

If one takes the above generalisations from hygrothermal analyses and looks at the results listed above, one may conclude as follows. For OSB and plywood products an average value from the lower and upper limits may be used for the vapour resistance factor and moisture diffusivity. The same may be true with the water absorption coefficient. But the equilibrium moisture content, especially in the higher rh regions may vary significantly and may need determination for every product, to make reliable input to hygrothermal models. Though air permeance can apparently vary, even the most leaky OSB or plywood is rather resistant to airflow and may not make significant errors in hygrothermal analyses, if one were to take an average value from what is reported here.

If wood fibreboard is part of a construction, the input to hygrothermal models will depend on whether the board consists of natural wood fibre, or it has surface coatings or facers. For composite wood sidings, one may have to determine all moisture transport and storage properties for each product, to make reliable input to hygrothermal models.

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9 REFERENCES

Annual Book of ASTM Standards 2001. C 518-98, Standard test method for steady-state thermal transmission properties by means of heat flow meter apparatus. 174-188.

Annual Book of ASTM Standards 2001. C 1498-01, Standard test method for hygroscopic sorption isotherms of building materials. 889-891.

Annual Book of ASTM Standards 2001. E 96-00, Standard test method for water vapor transmission of materials. 907-914.

Bomberg, M. T. & Kumaran, M.K. 1986. A Test method to determine air flow resistance of exterior membranes and sheathings. *Journal of Thermal Insulation*, Vol.9, pp. 224-235.

Bruce, R. R. & Klute, A. 1956. The Measurement of Soil Diffusivity. *Soil Science Society of America Proceedings*. Vol. 20, pp. 251-257.

Hansen, M. H. 1998. Retention Curves Measured Using Pressure Plate and Pressure Membrane. *Nordtest Technical Report 367*, Danish Building Research Institute, p 63.

Hens, H. 1996. Heat, Air and Moisture Transfer in Insulated Envelope Parts. Final Report, Volume 1, Task 1: Modelling. International Energy Agency Annex 24, Laboratorium Bouwfysica, K. U. -Leuven, Belgium.

Kumaran, M. K. 1996. Heat, Air and Moisture Transfer in Insulated Envelope Parts. Final Report, Volume 3, Task 3: Material Properties. International Energy Agency Annex 24, Laboratorium Bouwfysica, K. U. -Leuven, Belgium.

Kumaran, M. K. 1998. An Alternative Procedure for the Analysis of Data from the Cup Method Measurements for Determination of Water Vapour Transmission Properties. *Journal of Testing and Evaluation*, Vol. 26 , pp. 575-581.

Kumaran, M.K. & Bomberg, M.T. 1985. A Gamma-spectrometer for determination of density distribution and moisture distribution in building materials. *Moisture and Humidity: Measurement and Control in Science and Industry : Proceedings of International Symposium* (Washington, D.C., USA, 1985), pp. 485-90.

Kumaran, M.K., Mitalas, G.P., Kohonen, R. & Ojanen, T, 1989. Moisture transport coefficient of pine from gamma ray absorption measurements. *Collected Papers in Heat Transfer, 1989 : Winter Annual Meeting of the ASME* (San Francisco, CA, USA, 1989) , *(ASME Heat Transfer Division vol. 123).* pp. 179-183

Kumaran, M. K., Lackey, J. C., Normandin, N., van Reenen, D & Tariku, F. 2002a. Summary report from Task 3 of MEWS project. Institute for Research in Construction, NRC Canada (NRCC-45369), pp. 68.

Kumaran, M. K., Lackey, J. C., Normandin, N., van Reenen, D & Tariku, F. 2002b. A thermal and moisture transport property database for common building and insulating materials. ASHRAE website, Research Project Report 1018-RP.

Lackey, J. C., Marchand, R. G. & Kumaran, M. K., 1997. A Logical Extension of the ASTM Standard E96 to Determine the Dependence of Water Vapour Transmission on Relative Humidity. *Insulation Materials: Testing And Applications: Third Volume, ASTM STP 1320*, R. S. Graves and R. R. Zarr, (ed.), American Society for Testing and Materials, West Conshohocken, PA, pp 456-470.

Marchand, R.G. & Kumaran, M. K. 1994. Moisture diffusivity of cellulose insulation, *Journal of Thermal Insulation and Building Envelopes*, Vol. 17, pp. 362-377.

Trechsel, H. R. (ed) 2001.Moisture Analysis and Condensation Control in building envelopes. ASTM MNL40, Appendices A to K, 161-184.

Wang, J. & Kumaran, M.K. 1999. How well should one know the hygrotheraml properties of building materials? *Proceeding of CIB W40 Meeting* (Prague, Czech Republic), pp.47-52.