Hygrothermal Properties of Exterior Claddings, Sheathing Boards, Membranes, and Insulation Materials for Building Envelope Design

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ABSTRACT

Computer aided numerical simulation tools are now widely used to analyze the effects of heat-air-moisture (HAM) transport on the exterior building envelopes. However, these practical and user-friendly design tools obviously require reliable inputs to generate useful and meaningful information for the building envelope designers. One of these inputs is the detailed heat, air, and moisture transport properties of building envelope construction materials. Inherently, in case of building materials commonly used in North America, for the same generic building materials the properties may vary within a broad range. It is important that designers should acknowledge this phenomenon and incorporate this within the design parameters. This paper reports the density, thermal conductivity, equilibrium moisture content, water vapor permeability, water absorption coefficient, liquid diffusivity, and air permeability of twenty-three commonly used in North American building materials that include Exterior Claddings, Exterior Sheathing Boards, Membranes and Insulations. The experimental and analytical procedures, either international standards or well-established methodologies, used to determine these properties are also discussed in this paper.

INTRODUCTION

In North America many building envelopes fail prematurely during their service lives due to moisture related problems (Barrett, 1998). Forensic investigation of these failures is a complex process by any standard. Moreover, introduction of new building materials and building envelope systems has made this task even more challenging. Going back to the fundamentals of heat-air-moisture (HAM) transport is the only way to successfully meet these challenges. Application of hygrothermal simulation tools, based on the HAM fundamentals, for moisture design of exterior building envelopes could be very useful in such a situation (Mukhopadhyaya et al. 2006). The construction industry in North America has just started acknowledging this fact and many design practices now use hygrothermal simulation tools regularly. On many occasions application of hygrothermal simulation tools is handicapped due to the lack of reliable hygrothermal properties available for contemporary building materials. Hygrothermal material properties can vary widely for the same class of materials and appropriate determination of all these properties for a building material is not only technically challenging but also needs substantial time and resources. The Institute for Research in Construction (IRC) of the National Research Council (NRC) Canada has contributed substantially during the past ten tears to develop reliable hygrothermal material properties database (Kumaran et al. 2002; Kumaran 2006) that can be used by the design professionals to assess the moisture management performance of exterior building envelopes. The objective of this paper is to present a set of reliable and representative hygrothermal material properties, generated from a research project, of twenty-three building materials that are commonly used in North America for building envelope construction.

MATERIALS

The twenty-three selected materials used in this study are: (1) Exterior grade gypsum board, (2) Granite veneer, (3) Nepean sandstone, (4) EIFS base and finish coats, (5) Self

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adhesive membrane, A, (6) Self adhesive membrane, B, (7) Self adhesive membrane, C, (8) Torch applied asphalt based membrane, (9) Terra cotta clay tile, (10) High density mineral fibre insulation, (11) High density glass fiber insulation, (12) Foil faced polyisocyanurate, (13) Paper faced polyisocyanurate, (14) Reinforced concrete, (15) St. canut stone (sandstone), (16) Parge coating, (17) Fiber cement board, (18) Type 'O' mortar, (19) Tyndall limestone, (20) Pressed clay brick, (21) Cellulose fibre insulation, (22) Type 'K' mortar, and (23) Aged polyethylene film.

The hygrothermal properties of these materials have been determined following experimental and analytical techniques that comply with international standards or well-established peer-reviewed methodology. The NRC-IRC researchers have extensively researched upon these techniques for many years (Joy and Wilson, 1963; Shirtliffe 1980; Bomberg & Kumaran 1986; Kumaran 1989; Mukhopadhyaya et. al. 2002). The properties determined and procedures used to measure these material properties are documented in the following sections.

BASIC MATERIAL PROPERTIES AND TEST PROCEDURES

The following basic material properties have been investigated and documented in this study: (1) Dry density, (2) Thermal conductivity, (3) Equilibrium moisture content (Sorption, Desorption and Pressure Plate Measurements), (4) Water vapor permeability, (5) Water absorption coefficient, (6) Moisture diffusivity, and (7) Air permeability. The fundamentals behind these material properties and the measuring techniques are briefly outlined below.

Thermal Conductivity of Dry Materials

The heat conduction equation is directly used to determine the thermal conductivity of dry materials. Equipment that can maintain a known unidirectional steady state heat flux (under known constant boundary temperatures) across a flat slab of known thickness is used for the measurements. The most commonly used equipment is the guarded hot plate apparatus or the heat flow meter apparatus. The latter, following the ASTM standard C518, Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus, is used in this study. In the ASTM Standard, the heat conduction equation is written for practical applications as:

$$\lambda = Q \cdot l/(A \cdot \Delta T) \quad (1)$$

where

Q = heat flow rate across an area A

l = thickness of test specimen

ΔT = hot surface temperature – cold surface temperature

The thermal conductivity calculated according to [1] is called apparent thermal conductivity. It is a function of the average temperature of the test specimen.

Equilibrium Moisture Content from Sorption/ Desorption Measurements

Sorption/desorption characteristics are defined by determining the equilibrium moisture content in the material at different relative humidity (RH) levels. For sorption measurements, the dried specimen is placed consecutively in a series of test environments at constant temperature, with relative humidity increasing in stages, until equilibrium is reached in each environment. The starting point for the desorption measurements is from an equilibrium condition very close to 100% RH; then the specimen is placed consecutively in a series of test environments, with relative humidity decreasing in stages, until equilibrium is reached in each environment. ASTM Standard C 1498, Standard Test Method for Hygroscopic Sorption Isotherms of Building Materials, is used in this study to determine sorption/desorption characteristics of building materials.

Equilibrium Moisture Content from Pressure Plate (Desorption) Measurements

The test specimens are saturated with water under vacuum. Those are then introduced in a pressure plate apparatus that can maintain pressures up to 100 bar for several days. The plates in perfect hygric contact with the specimens extract water out of the pore structure until an equilibrium state is established. The equilibrium values for moisture contents in the specimens and the corresponding pressures (measured as the excess over atmospheric pressure; the negative of this value is referred to as the pore pressure while the absolute value is the suction) are recorded. The equilibrium pressure, p_h, can be converted to a relative humidity, φ, using the following equation:

$$\ln\varphi = -\frac{M}{\rho RT}p_h \quad (2)$$

where

M = the molar mass of water

R = the ideal gas constant

T = the thermodynamic temperature and

ρ = the density of water

A Nordtest Technical Report (Hansen 1998) that describes the procedure for pressure plate measurements has been used in this study.

Water Vapor Permeability

The vapor diffusion equation is directly used to determine the water vapor permeability of building materials (Joy and Wilson, 1963). The measurements are usually done under isothermal conditions. A test specimen of known area and thickness separates two environments that differ in relative humidity (RH). Then the rate of vapor flow across the specimen, under steady-state conditions (known RHs as constant boundary conditions), is gravimetrically determined. From these data the water vapor permeability of the material is calculated as:

$$\delta_p = J_v \cdot l/(A \cdot \Delta p) \quad (3)$$

where

J_v = water vapor flow rate across an area A

l = thickness of the specimen

Δp = difference in water vapor pressure across the specimen surfaces

Water vapor permeance, δ_l, of a product at a given thickness is calculated from the above measurements as:

$$\delta_l = J_v/(A \cdot \Delta p) \quad (4)$$

ASTM standard E96, Standard Test Methods for Water Vapor Transmission of Materials, prescribes two specific cases of this procedure:

1. Dry cup method that gives the permeance or permeability at a mean RH of 25%, and
2. Wet cup method that gives the permeance or permeability at a mean RH of 75%.

In principle, the ASTM E96 test method has been used in this study. However, in order to satisfy the requirements of advanced hygrothermal modelling tools, additional measurements have been done using the same test method to establish the functional relationship of water vapor permeability with the relative humidity as outlined in the literature (Kumaran, 1998).

Water Absorption Coefficient

In order to determine water absorption coefficient, one major surface of each test specimen is placed in contact with liquid water. The increase in mass as a result of moisture absorption is recorded as a function of time. Usually, during the initial part of the absorption process a plot of the mass increase against the square root of time is linear. The slope of the line divided by the area of the surface in contact with water is the water absorption coefficient. When this method is applied to membranes, the membranes are usually put in perfect hygric contact with a substrate such as wood.

A new European Standard ISO 15148:2002(E), Hygrothermal Performance of Building Materials and Products - Determination of Water Absorption Coefficient by Partial Immersion, prescribes the details on the determination of water absorption coefficient of building materials.

Moisture Diffusivity

Moisture diffusivity, D_w, defines the rate of movement of water, J_l, within a material, induced by a water concentration gradient according to the following equation:

$$J_l = -\rho^0 D_w gradu \quad (5)$$

where

ρ^0 = density of the dry material, and

u = moisture content expressed as mass of water / dry mass of material.

In the experimental procedure, liquid water in contact with one surface of a test specimen is allowed to diffuse into the specimen. The distribution of moisture within the specimen is determined as a function of time at various intervals until the moving moisture front advances to half of the specimen. Gamma spectroscopy is used as the experimental technique. The data are analyzed using the Boltzmann transformation (Bruce and Klute, 1956; Kumaran et al. 1989) to derive the moisture diffusivity as a function of moisture content.

There is no standard test procedure for the determination of moisture diffusivity. There are many publications in the literature that describe the technical and experimental details (Merchand and Kumaran 1994; Kumaran and Bomberg 1985; Descamps 1997).

Air Permeability

Test specimens with known areas and thickness are positioned to separate two regions that differ in air pressure and the airflow rate at a steady state and the pressure differential across the specimen are recorded. From these data the air permeability, k_a is calculated as:

$$k_a = J_a \cdot l/(A \cdot \Delta p) \quad (6)$$

where

J_a = air flow rate across an area A,

l = thickness of the specimen, and

Δp = difference in air pressure across the specimen surfaces.

Often, especially for membranes and composite materials, one calculates the air permeance, K_a, of a product at a given thickness from the above measurements as:

$$K_a = J_a/(A \cdot \Delta p) \quad (7)$$

ASTM Standard C 522, Standard Test Method for Airflow Resistance of Acoustical Materials, prescribes a method based on this principle. Bomberg and Kumaran (1986) have extended the method for general application to building materials

HYGROTHERMAL PROPERTIES OF BUILDING MATERIALS

The following eleven (11) exterior cladding or cladding related materials, two (2) sheathing boards, five (5) membranes, and five (5) insulation materials have been considered in this study.

Exterior Claddings: (1) Granite veneer, (2) Nepean sandstone, (3) EIFS base and finish coats, (4) Terra cotta clay tile, (5) Reinforced concrete, (6) St. canut stone (sandstone), (7) Parge coating, (8) Type ‘O’ mortar, (9) Tyndall limestone, (10) Pressed clay brick, and (11) Type ‘K’ mortar.

Sheathing Boards: (1) Exterior grade gypsum board, and (2) Fibre cement board.

Membranes: (1) Self adhesive membrane, A, (2) Self adhesive membrane, B, (3) Self adhesive membrane, C, (4) Torch applied asphalt based membrane, and (5) Aged polyethylene film.

Insulations: (1) High density mineral fiber insulation, (2) High density glass fiber insulation, (3) Foil faced polyisocyanurate, (4) Paper faced polyisocyanurate, and (5) Cellulose fiber insulation.

The material specimens were dried as specified in the ASTM C1498, Standard Test Method for Hygroscopic Sorption Isotherms of Building Material, and basic material properties such as thickness and density of all cladding materials were determined shown in the Table 1.

Thermal Conductivity

Two 30 cm × 30 cm test specimens of exterior claddings were precision-cut for uniform thickness. Highly compressible thermal pads were placed between the specimens and the plates of the heat flow meter apparatus to minimize the effect of contact resistances. Also, thermocouples were placed to measure the surface temperatures of the test specimens. The uncertainty in the thermal conductivities derived from these measurements may be as high as 5%. (For thermal insulation materials, the same equipment yields thermal conductivities that are accurate within 2.5%). Thermal conductivity of a material is known to vary significantly as a function of temperature and hence, measurements were done at two different mean temperatures as listed in Table 2. It is to be noted here that the thermal properties of the membrane materials have no practical bearing on the overall hygrothermal response of the wall systems and therefore not measured in this study.

Equilibrium Moisture Content

Three specimens each were used for sorption and desorption measurements and nine specimens were used in the pressure plate (suction) measurements. A set of constant temperature (23 ± 0.3 °C) and constant relative humidity chambers (controlled within 0.5%) were used for the sorption/desorption measurements. The suction measurements were performed at laboratory conditions, 21± 0.5 °C. For the pressure plate measurements separate set of specimens were used. The starting point was vacuum saturation. The results from these measurements are listed in Tables 3a, 3b and 3c. These results indicate that there could be considerable difference between sorption and desorption equilibrium moisture content of the cladding materials. At the same time, it is also to be mentioned that equilibrium moisture contents of five (5) membranes were not determined in this study, as they would have no significant influence on the overall moisture response of the wall assemblies.

Table 1. Thickness and Density of Materials

Material	Approximate Thickness, mm	Density, $kg \cdot m^{-3}$
Granite veneer	20	2850
Nepean sandstone	14	2380
EIFS base and finish coats	4	1150
Terra cotta clay tile,	15	1826
Reinforced concrete	50	2330
St. canut stone (sandstone)	20	2495
Parge coating	23	1699
Type 'O' mortar	13	1661
Tyndall limestone	14	2338
Pressed clay brick	17	1862
Type 'K' mortar	15	1532
Exterior grade gypsum board	12	625
Fibre cement board	7	1424
Self adhesive membrane, A	0.8	1023
Self adhesive membrane, B	1.1	956
Self adhesive membrane, C	1.3	964
Torch applied asphalt based membrane	2.4	1176
Aged polyethylene film	0.14	948
High density mineral fibre insulation	*	85.17
High density glass fibre insulation	*	72.19
Foil faced polyisocyanurate	27	33.57
Paper faced polyisocyanurate	27	63.01
Cellulose fibre insulation	*	25.7

*Not applicable.

Water Absorption Coefficient

For all specimens, the major surfaces were parallel to the faces of the cladding and the water absorption was perpendicular to those surfaces. All measurements were done at a water temperature of 22 ± 0.5°C. The results from these measurements are listed in Table 4. The water absorption coefficient of aged polyethylene membrane could not be measured because of its insignificant water absorption capacity. The water absorption coefficients of insulation materials were also not measurable for the similar practical reasons.

Water Vapor Permeability

All measurements were done at 23±0.3°C on six specimens of each material. Three specimens of each cladding material were used for a series of three dry cup (desiccant method) measurements with the chamber RH equal to approximately 50% or 70% or 90%. The other three specimens were used for a series of two wet cup (water method) measurements with the chamber RH equal to approximately 70% or 90%. At each test condition the RH was maintained within 0.5% for the duration of each measurement. From the 15 results so obtained on each material the dependence of water vapor permeability on RH for that material was derived (Kumaran, 1998). The results are listed in Tables 5a and 5b.

Liquid (Moisture) Diffusivity

The rectangular test specimens (20 cm × 6.5 cm) were used for the gamma-ray measurements. The specimens were cut with their surfaces parallel to the major surface of each cladding material. The liquid water uptake was parallel to the major surfaces and hence parallel to the major surfaces of the claddings.

The results from the gamma-ray measurements that show the dependence of liquid diffusivity (D_{w}) on local moisture content are listed in Tables 6a and 6b.

However for Granite Veneer the moisture content was too small to be detected by gamma ray attenuation technique. However, based on the Information on saturation water content from Table 3a and on water absorption coefficient from Table 4, the estimated average liquid diffusivity (Kumaran, 1999) perpendicular to the major surface is estimated to be 2.013 x 10^{-11} m^2 s^{-1}. The liquid diffusivity of five (5) membrane materials and five (5) insulation materials were not determined for practical reasons.

Air Permeability

The test specimens (three for each material) used in these measurements were identical to those used for the water vapor permeability measurements. However, pressure differences up to 5 kPa did not yield any measurable airflow rates for some materials. The chambers that carried the test specimens (Bomberg and Kumaran, 1986) were pressurized and from the pressure decay rates the air permeabilities were estimated. All measurements were done at 21 ± 0.5°C. The results are listed in Table 7. The air permeability of the self-adhesive membranes and the polyisocyanurate (closed-cell foam) insulations were found to be too impermeable to measure.

CONCLUDING REMARKS

The material properties presented in this paper indicate that the hygrothermal response characteristics of the building materials could be significantly different though they have same functional role in managing heat, air, and moisture transport through the building envelopes. Obviously, the effect of these material properties variations needs to be investigated further using advanced hygrothermal modeling tools.

The range of properties shown in this paper clearly suggests that the building envelope designer must be very careful about choosing the basic materials for the exterior building envelope construction. Availability of the realistic material property database and use of benchmarked modeling tools can assist a designer to select the most suitable building materials for the optimum moisture management in the exterior building envelopes. Hence, it is hoped that the information presented in this paper will help the building envelope designers to carry out parametric analyses and establish the sensitivity of the final results to variations in the hygrothermal properties of various building materials.

Table 2. Thermal Conductivity of Building Materials

Material	Thermal Conductivity ($W.m^{-1}.K^{-1}$)	
Granite veneer	0.71 at 4.8°C	0.74 at 26.9°C
Nepean sandstone	0.92 at 4.0°C	0.99 at 24.8°C
EIFS base and finish coats	0.59 at 0.0°C	0.59 at 23.0°C
Terra cotta clay tile	0.36 at 3.3°C	0.38 at 24.5°C
Reinforced concrete	1.08 at -2.3°C	1.08 at 24.4°C
St. canut stone (sandstone)	1.01 at -2.3°C	1.04 at 22.0°C
Parge coating	0.37 at 0.5°C	0.38 at 21.4°C
Type 'O' mortar	0.34 at 10.9°C	0.34 at 26.8°C
Tyndall limestone	1.04 at 9.4°C	1.05 at 25.7°C
Pressed clay brick	0.45 at 9.6°C	0.45 at 26.0°C
Type 'K' mortar	0.36 at 9.8°C	0.36 at 25.7°C
Exterior grade gypsum board	0.14 at 4.4°C	0.14 at 26.7°C
Fiber cement board	0.24 at 10.4°C	0.24 at 24.9°C
Self adhesive membrane, A	Not measured	Not measured
Self adhesive membrane, B	Not measured	Not measured
Self adhesive membrane, C	Not measured	Not measured
Torch applied asphalt based membrane	Not measured	Not measured
Aged polyethylene film.	Not measured	Not measured
High density mineral fiber insulation	0.03 at 0°C	0.033 at 23.9°C
High density glass fiber insulation	0.029 at 0.4°C	0.031 at 24°C
Foil faced polyisocyanurate	0.023 at 0.4°C	0.025 at 23.9°C
Paper faced polyisocyanurate,	0.029 at 0.4°C	0.028 at 24°C
Cellulose fiber insulation.	0.034 at 0°C	0.038 at 23.9°C

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REFERENCES

ASTM E 96/E 96M – 05. 2005. Standard Test Methods for Water Vapor Transmission of Materials. *ASTM Interna-*

Table 3a. Equilibrium Moisture Contents of Building Materials at Various Relative Humidities (RH)

Granite Veneer		Nepean Sandstone		EIFS Base and Finish Coats		Terra Cotta Clay Tile		Reinforced Concrete		St. Canut Stone (Sandstone)	
RH, %	Moisture Content, $kg \cdot kg^{-1}$	RH, %	Moisture Content, $kg \cdot kg^{-1}$	RH, %	Moisture Content, $kg \cdot kg^{-1}$	RH, %	Moisture Content, $kg \cdot kg^{-1}$	RH, %	Moisture Content, $kg \cdot kg^{-1}$	RH, %	Moisture Content, $kg \cdot kg^{-1}$
50.6 (sorp.)	0.0011	50.2 (sorp.)	0.0004	50 (sorp.)	0.0194	50.1(sorp.)	0.0013	50.2 (sorp.)	Not measured	50.2 (sorp.)	0.0001
70.0 (sorp.)	0.0014	70.0 (sorp.)	0.0003	70 (sorp.)	0.0262	70.3(sorp.)	0.0015	70.0 (sorp.)	Not measured	70.0 (sorp.)	0.0001
88.4 (sorp.)	0.0015	88.4 (sorp.)	0.0009	90 (sorp.)	0.0434	89.0 (sorp.)	0.0025	88.4 (sorp.)	Not measured	88.4 (sorp.)	0.0001
50 (desorp.)	0.0014	50.2 (desorp.)	0.0003	50 (desorp.)	Not measured	50.1(desorp.)	0.0030	95.4 (sorp.)	0.0618	95.4 (sorp.)	0.0003
70 (desorp.)	0.0015	70.0 (desorp.)	0.0004	70 (desorp.)	Not measured	70.3(desorp.)	0.0029	50.2 (desorp.)	0.0355	50.2 (desorp.)	0.0000
90 (desorp.)	0.0016	88.4 (desorp.)	0.0009	90 (desorp.)	Not measured	89.0(desorp.)	0.0043	70.1 (desorp.)	0.0417	70.1 (desorp.)	0.0000
98.901 (suct.)	0.0015	98.90 (suct.)	0.0019	92 (suct.)	0.0474	99.193 (suct.)	0.0041	88.4 (desorp.)	0.0508	88.4 (desorp.)	0.0002
99.193 (suct.)	0.0015	99.19 (suct.)	0.0026	94 (suct.)	0.0527	99.268 (suct.)	0.0073	95.4 (desorp.)	0.0653	95.4 (desorp.)	0.0003
99.268 (suct.)	0.0015	99.27 (suct.)	0.0030	96 (suct.)	0.0603	99.500 (suct.)	0.0162	100 (desorp.)	0.1031	100 (desorp.)	0.0227
99.500 (suct.)	0.0014	99.50 (suct.)	0.0041	98 (suct.)	0.0724	99.595 (suct.)	0.0207	98.9 (suct.)	0.0906	98.9 (suct.)	0.0014
99.595 (suct.)	0.0015	99.60 (suct.)	0.0050	100 (suct.)	0.0896	99.779 (suct.)	0.0392	99.27 (suct.)	0.0939	99.27 (suct.)	0.0017
99.706 (suct.)	0.0014	99.71 (suct.)	0.0067			99.85 (suct.)	0.0622	99.6 (suct.)	0.0969	99.6 (suct.)	0.0028
99.779 (suct.)	0.0014	99.78 (suct.)	0.0084			99.926 (suct.)	0.0720	99.71 (suct.)	0.0942	99.71 (suct.)	0.0031
99.85 (suct.)	0.0014	99.85 (suct.)	0.0058			100.000 (suct.)	0.0963	99.78 (suct.)	0.0950	99.78 (suct.)	0.0038
99.926 (suct.)	0.0014	99.93 (suct.)	0.0084					99.85 (suct.)	0.1017	99.85 (suct.)	0.0049
100.000 (suct.)	0.0043	100.00 (suct.)	0.0493					99.93 (suct.)	0.1019	99.93 (suct.)	0.0063
								100 (suct.)	0.1053	100 (suct.)	0.0256

Table 3b. Equilibrium Moisture Contents of Building Materials at Various Relative Humidities (RH)

Parge Coating		Type 'O' Mortar		Tyndall Limestone		Pressed Clay Brick		Type 'K' Mortar		Exterior Grade Gypsum Board	
RH, %	Moisture Content, kg·kg^{-1}	RH, %	Moisture Content, kg·kg^{-1}	RH, %	Moisture Content, kg·kg^{-1}	RH, %	Moisture Content, kg·kg^{-1}	RH, %	Moisture Content, kg·kg^{-1}	RH, %	Moisture Content, kg·kg^{-1}
50.2 (sorp.)	0.0030	50.2 (sorp.)	0.016	50.2 (sorp.)	0.0001	50.2 (sorp.)	0.0014	50.2 (sorp.)	0.005	50.1 (sorp.)	0.0048
70.0 (sorp.)	0.0089	69.8 (sorp.)	0.028	69.8 (sorp.)	0.0002	69.8 (sorp.)	0.0019	69.8 (sorp.)	0.010	70.3 (sorp.)	0.0069
88.4 (sorp.)	0.0170	89.9 (sorp.)	0.058	89.9 (sorp.)	0.0004	89.9 (sorp.)	0.0019	89.9 (sorp.)	0.022	88.6 (sorp.)	0.0175
95.4 (sorp.)	0.0183	94.5 (sorp.)	0.064	94.5 (sorp.)	0.0005	94.5 (sorp.)	0.0021	94.5 (sorp.)	0.025	Not feasible*	Not feasible*
50.2 (desorp.)	0.0027	50.2 (desorp.)	0.020	50.2 (desorp.)	0.0000	50.2 (desorp.)	0.0027	50.2 (desorp.)	0.007	Not feasible	Not feasible
70.1 (desorp.)	0.0085	69.9 (desorp.)	0.030	69.9 (desorp.)	0.0000	69.9 (desorp.)	0.0026	69.9 (desorp.)	0.008	Not feasible	Not feasible
88.4 (desorp.)	0.0126	90.0 (desorp.)	0.048	90.0 (desorp.)	0.0003	90.0 (desorp.)	0.0032	90.0 (desorp.)	0.020		
95.4 (desorp.)	0.0172	94.5 (desorp.)	0.058	94.5 (desorp.)	0.0002	94.5 (desorp.)	0.0035	94.5 (desorp.)	0.025		
100 (desorp.)	0.1920	100 (desorp.)	0.185	100 (desorp.)	0.052	100 (desorp.)	0.1453	100 (desorp.)	0.198		
98.9 (suct.)	0.0518	98.90 (suct.)	0.086	98.90 (suct.)	0.003	98.90 (suct.)	0.028	98.90 (suct.)	0.045		
99.27 (suct.)	0.0556	99.41 (suct.)	0.098	99.41 (suct.)	0.004	99.41 (suct.)	0.056	99.41 (suct.)	0.053		
99.6 (suct.)	0.0671	99.63 (suct.)	0.110	99.63 (suct.)	0.007	99.63 (suct.)	0.079	99.63 (suct.)	0.062		
99.71 (suct.)	0.0649	99.71 (suct.)	0.118	99.71 (suct.)	0.009	99.71 (suct.)	0.084	99.71 (suct.)	0.071		
99.78 (suct.)	0.0706	99.78 (suct.)	0.124	99.78 (suct.)	0.013	99.78 (suct.)	0.102	99.78 (suct.)	0.080		
99.85 (suct.)	0.1105	99.85 (suct.)	0.127	99.85 (suct.)	0.017	99.85 (suct.)	0.116	99.85 (suct.)	0.100		
99.93 (suct.)	0.1197	99.93 (suct.)	0.139	99.93 (suct.)	0.033	99.93 (suct.)	0.126	99.93 (suct.)	0.126		
100 (suct.)	0.1930	100 (suct.)	0.176	100 (suct.)	0.052	100 (suct.)	0.147	100 (suct.)	0.198		

*Exterior grade gypsum board cannot be saturated without disintegration.

Table 3c. Equilibrium Moisture Contents of Building Materials at Various Relative Humidities (RH)

Fiber Cement Board		High Density Mineral Fiber Insulation		High Density Glass Fiber Insulation		Foil Faced Polyisocyanurate		Paper Faced Polyisocyanurate		Cellulose Fiber Insulation	
RH, %	Moisture Content, $kg \cdot kg^{-1}$	RH, %	Moisture Content, $kg \cdot kg^{-1}$	RH, %	Moisture Content, $kg \cdot kg^{-1}$	RH, %	Moisture Content, $kg \cdot kg^{-1}$	RH, %	Moisture Content, $kg \cdot kg^{-1}$	RH, %	Moisture Content, $kg \cdot kg^{-1}$
50.2 (sorp.)	0.029	50.2 (sorp.)	0.0005	50.2 (sorp.)	0.0041	50.2 (sorp.)	0.0059	50.2 (sorp.)	0.0030	50.5 (sorp.)	0.061
69.8 (sorp.)	0.041	70.0 (sorp.)	0.0009	70.0 (sorp.)	0.0063	70.0 (sorp.)	0.0110	70.0 (sorp.)	0.0055	71.5 (sorp.)	0.096
89.9 (sorp.)	0.099	88.4 (sorp.)	0.0009	88.4 (sorp.)	0.0226	88.4 (sorp.)	0.0197	88.4 (sorp.)	0.0110	88.1 (sorp.)	0.240
94.5 (sorp.)	0.114	95.4 (sorp.)	0.0012	95.4 (sorp.)	0.0411	95.4 (sorp.)	0.0248	95.4 (sorp.)	0.0202	50.2 (desorp.)	0.050
50.2 (desorp.)	0.053	50.2 (desorp.)	0.0000	50.2 (desorp.)	0.0018	50.2 (desorp.)	0.0078	50.2 (desorp.)	0.0016	72.8 (desorp.)	0.120
69.9 (desorp.)	0.074	70.1 (desorp.)	0.0013	70.1 (desorp.)	0.0039	70.1 (desorp.)	0.0158	70.1 (desorp.)	0.0046	88.0 (desorp.)	0.260
90.0 (desorp.)	0.153	88.4 (desorp.)	0.0024	88.4 (desorp.)	0.0165	88.4 (desorp.)	0.0282	88.4 (desorp.)	0.0081		
94.5 (desorp.)	0.179	95.4 (desorp.)	0.0098	95.4 (desorp.)	0.0238	95.4 (desorp.)	0.0315	95.4 (desorp.)	0.0106		
100 (desorp.)	0.294	100 (desorp.)	6.665	100 (desorp.)	6.9280	100 (desorp.)	0.2948	100 (desorp.)	0.2257		
98.90 (suct.)	0.211										
99.41 (suct.)	0.215										
99.63 (suct.)	0.219										
99.71 (suct.)	0.222										
99.78 (suct.)	0.226										
99.85 (suct.)	0.235										
99.93 (suct.)	0.254										
100 (suct.)	0.299										

Table 4. Water Absorption Coefficients of Building Materials

Material	Water Absorption Coefficient, $kg \cdot m^{-2} \cdot s^{-0.5}$	Material	Water Absorption Coefficient, $kg \cdot m^{-2} \cdot s^{-0.5}$	Material	Water Absorption Coefficient, $kg \cdot m^{-2} \cdot s^{-0.5}$	Material	Water Absorption Coefficient, $kg \cdot m^{-2} \cdot s^{-0.5}$
Granite veneer	$9.69x10^{-5} \pm 8.40x10^{-6}$	Parge coating	$8.107\times10^{-02} \pm 2.788\times10^{-03}$	Fiber cement board	$11.4\times10^{-3} \pm 6.8\times10^{-5}$	High density mineral fiber insulation	Not Measurable
Nepean sandstone	0.0033±0.0001	Type 'O' mortar	$12.65\times10^{-2} \pm 3.70x10^{-4}$	Self adhesive membrane, A	$6.505\times10^{-05} \pm 2.394\times10^{-06}$	High density glass fiber insulation	Not Measurable
EIFS base and finish coats	$4.85\times10^{-04} \pm 8.21\times10^{-06}$	Tyndall limestone	$2.14\times10^{-2} \pm 1.0\times10^{-4}$	Self adhesive membrane, B	$5.970\times10^{-05} \pm 2.714\times10^{-06}$	Foil faced polyisocyanurate	Not Measurable
Terra cotta clay tile	0.109±0.006	Pressed clay brick	$1.04\times10^{-1} \pm 1.5\times10^{-3}$	Self adhesive membrane, C	$6.394\times10^{-05} \pm 2.475\times10^{-06}$	Paper faced polyisocyanurate	Not Measurable
Reinforced concrete	$1.861\times10^{-02} \pm 1.284\times10^{-04}$	Type 'K' mortar	$2.72\times10^{-1} \pm 3.5\times10^{-3}$	Torch applied asphalt based membrane	$6.008\times10^{-05} \pm 2.049\times10^{-06}$	Cellulose fiber insulation	Not Measurable
St. canut stone (sandstone)	$7.004\times10^{-03} \pm 8.95\times10^{-05}$	Exterior grade gypsum board	0.18 ± 0.02	Aged polyethylene film	Not Measured (Insignificant)		

Table 5a. Water Vapor Permeability of Building Materials at Various Relative Humidities (RH)

RH, %	Water Vapor Permeability, $kg \cdot m^{-1} \cdot s^{-1} \cdot Pa^{-1}$										
	Granite Veneer	Nepean Sandstone	EIFS Base and Finish Coats	Terra Cotta Clay Tile	Reinforced Concrete	St. Canut Stone (Sandstone)	Parge Coating	Type 'O' Mortar	Tyndall Limestone	Pressed Clay Brick	Type 'K' Mortar
10	7.17E-15	1.55E-12	3.50E-12	6.39E-12	9.28E-13	1.82E-15	1.39E-11	1.38E-11	1.76E-12	5.96E-12	2.28E-11
20	1.14E-14	1.59E-12	3.50E-12	6.68E-12	1.08E-12	5.34E-15	1.49E-11	1.47E-11	1.99E-12	6.17E-12	2.38E-11
30	1.63E-14	1.62E-12	3.50E-12	6.98E-12	1.26E-12	1.57E-14	1.60E-11	1.56E-11	2.24E-12	6.40E-12	2.48E-11
40	2.32E-14	1.65E-12	3.50E-12	7.30E-12	1.48E-12	4.59E-14	1.72E-11	1.65E-11	2.53E-12	6.63E-12	2.59E-11
50	3.37E-14	1.62E-12	3.50E-12	7.63E-12	1.73E-12	1.35E-13	1.85E-11	1.76E-11	2.86E-12	6.86E-12	2.71E-11
60	5.17E-14	1.45E-12	3.50E-12	7.98E-12	2.02E-12	3.96E-13	1.99E-11	1.87E-11	3.22E-12	7.11E-12	2.83E-11
70	8.73E-14	1.43E-12	3.50E-12	8.35E-12	2.36E-12	1.17E-12	2.14E-11	1.98E-11	3.64E-12	7.37E-12	2.96E-11
80	1.75E-13	3.79E-12	3.50E-12	8.73E-12	2.76E-12	3.49E-12	2.30E-11	2.11E-11	4.11E-12	7.64E-12	3.09E-11
90	4.99E-13	1.93E-11	3.50E-12	9.13E-12	3.22E-12	1.08E-11	2.48E-11	2.25E-11	4.65E-12	7.91E-12	3.23E-11
100	5.21E-12	1.44E-10	3.50E-12	9.56E-12	3.77E-12	3.78E-11	2.67E-11	2.39E-11	5.26E-12	8.20E-12	3.38E-11

Table 5b. Water Vapor Permeability of Building Materials at Various Relative Humidities (RH)

RH, %	Water Vapor Permeability ($kg.m^{-1}.s^{-1}.Pa^{-1}$)											
	Exterior Grade Gypsum Board	Fiber Cement Board	Self Adhesive Membrane, A	Self Adhesive Membrane, B	Self Adhesive Membrane, C	Torch Applied Asphalt Based Membrane	Aged Polyethylene Film	High Density Mineral Fiber Insulation	High Density Glass Fiber Insulation	Foil Faced Polyisocyanurate	Paper Faced Polyisocyanurate	Cellulose Fiber Insulation
10	3.59E-11	2.01E-13	1.07E-15	1.69E-15	2.16E-15	1.52E-15	4.81E-16	1.40E-10	1.39E-10	1.16E-13	1.54E-12	1.23E-10
20	3.75E-11	3.38E-13	1.18E-15	1.80E-15	2.34E-15	2.05E-15	4.81E-16	1.40E-10	1.39E-10	1.16E-13	1.61E-12	1.29E-10
30	3.92E-11	5.68E-13	1.30E-15	1.93E-15	2.53E-15	2.58E-15	4.81E-16	1.40E-10	1.39E-10	1.16E-13	1.69E-12	1.36E-10
40	4.10E-11	9.56E-13	1.43E-15	2.07E-15	2.73E-15	3.11E-15	4.81E-16	1.40E-10	1.39E-10	1.16E-13	1.77E-12	1.42E-10
50	4.29E-11	1.62E-12	1.57E-15	2.21E-15	2.96E-15	3.65E-15	4.81E-16	1.40E-10	1.39E-10	1.16E-13	1.85E-12	1.50E-10
60	4.48E-11	2.76E-12	1.73E-15	2.37E-15	3.20E-15	4.18E-15	4.81E-16	1.40E-10	1.39E-10	1.16E-13	1.94E-12	1.57E-10
70	4.70E-11	4.76E-12	1.91E-15	2.53E-15	3.45E-15	4.71E-15	4.81E-16	1.40E-10	1.39E-10	1.16E-13	2.04E-12	1.65E-10
80	4.92E-11	8.41E-12	2.10E-15	2.71E-15	3.74E-15	5.24E-15	4.81E-16	1.40E-10	1.39E-10	1.16E-13	2.13E-12	1.74E-10
90	5.16E-11	1.55E-11	2.31E-15	2.90E-15	4.04E-15	5.78E-15	4.81E-16	1.40E-10	1.39E-10	1.16E-13	2.24E-12	1.83E-10
100	5.41E-11	3.13E-11	2.54E-15	3.10E-15	4.37E-15	6.31E-15	4.81E-16	1.40E-10	1.39E-10	1.16E-13	2.34E-12	1.93E-10

Table 6a. Liquid (Moisture) Diffusivity of Building Materials

Nepean Sandstone		Terra Cotta Clay Tile		Reinforced Concrete (Contd.)		Parge Coating (Contd.)		Type 'O' Mortar (Contd.)		Pressed Clay Brick (Contd.)		Type 'K' Mortar (Contd.)	
Moisture Content, $kg \cdot kg^{-1}$	**Diffusivity, $m^2 \cdot s^{-1}$**	**Moisture Content, $kg \cdot kg^{-1}$**	**Diffusivity, $m^2 \cdot s^{-1}$**	**Moisture Content, $kg \cdot kg^{-1}$**	**Diffusivity, $m^2 \cdot s^{-1}$**	**Moisture Content, $kg \cdot kg^{-1}$**	**Diffusivity, $m^2 \cdot s^{-1}$**	**Moisture Content, $kg \cdot kg^{-1}$**	**Diffusivity, $m^2 \cdot s^{-1}$**	**Moisture Content, $kg \cdot kg^{-1}$**	**Diffusivity, $m^2 \cdot s^{-1}$**	**Moisture Content, $kg \cdot kg^{-1}$**	**Diffusivity, $m^2 \cdot s^{-1}$**
4.20E-03	1.494E-09	2.74E-02	4.35E-08	20	3.02E-10	30	4.14E-08	100	4.48E-08	40	2.85E-08	110	3.56E-07
8.40E-03	2.623E-09	3.29E-02	4.93E-08	30	2.64E-10	40	4.42E-08	110	5.26E-08	50	3.44E-08	120	5.91E-07
1.26E-02	2.783E-09	3.83E-02	5.51E-08	40	2.37E-10	50	4.61E-08	120	6.3E-08	60	4.04E-08	130	2.53E-06
2.10E-02	1.163E-09	4.38E-02	6.09E-08	50	2.16E-10	60	4.75E-08	**Tyndall Limestone**		70	4.7E-08	140	9.02E-07
2.52E-02	7.960E-10	4.93E-02	6.69E-08	60	1.99E-10	70	4.87E-08	5	3.28E-08	80	5.45E-08	150	5.97E-07
2.94E-02	6.265E-10	5.48E-02	7.30E-08	70	1.84E-10	80	5E-08	10	3.89E-08	90	6.34E-08	160	5.19E-07
3.36E-02	5.247E-10	6.02E-02	7.94E-08	80	1.72E-10	90	5.14E-08	15	3.93E-08	100	7.41E-08	170	5.12E-07
3.78E-02	4.550E-10	6.57E-02	8.61E-08	90	1.61E-10	100	5.32E-08	20	3.87E-08	110	8.75E-08	180	5.75E-07
4.20E-02	4.033E-10	7.12E-02	9.31E-08	100	1.51E-10	110	5.55E-08	25	3.82E-08	120	1.05E-07	190	8.40E-07
Eifs Base and Finish Coats		7.67E-02	1.01E-07	110	1.42E-10	120	5.86E-08	30	3.82E-08	130	1.27E-07	200	1.27E-06
1.83E-03	1E-16	8.21E-02	1.09E-07	120	1.33E-10	130	6.28E-08	35	3.9E-08	140	1.58E-07	**Exterior Grade Gypsum Board**	
7.31E-03	1E-16	8.76E-02	1.18E-07	130	1.26E-10	140	6.86E-08	40	4.07E-08	150	2.01E-07	1.60E-02	8.83E-09
1.28E-02	1E-16	9.31E-02	1.27E-07	140	1.19E-10	150	7.7E-08	45	4.34E-08	160	2.64E-07	3.20E-02	1.80E-08
1.83E-02	1E-16	9.86E-02	1.38E-07	150	1.12E-10	160	8.99E-08	50	4.75E-08	170	3.62E-07	4.80E-02	2.74E-08
2.38E-02	1E-16	1.04E-01	1.50E-07	**St. Canut Stone (Sandstone)**		170	1.12E-07	55	5.34E-08	180	5.25E-07	6.40E-02	3.72E-08
2.92E-02	1E-16	1.10E-01	1.64E-07	2	1.57E-09	180	1.55E-07	60	6.18E-08	190	8.26E-07	8.00E-02	4.74E-08
3.47E-02	1E-16	1.15E-01	1.80E-07	4	2.39E-09	190	2.80E-07	65	7.41E-08	200	1.48E-06	9.60E-02	5.79E-08
4.02E-02	1E-16	1.20E-01	1.99E-07	6	2.74E-09	200	3.88E-06	70	9.25E-08	**Type 'K' Mortar**		1.12E-01	6.88E-08
4.57E-02	1E-16	1.26E-01	2.24E-07	8	2.79E-09	**Type 'O' Mortar**		75	1.21E-07	10	1.04E-08	1.28E-01	8.01E-08
5.12E-02	1E-16	1.31E-01	2.54E-07	10	2.66E-09	10	6.55E-09	80	1.7E-07	20	2.23E-08	1.44E-01	9.18E-08
5.30E-02	1E-16	1.37E-01	2.95E-07	12	2.43E-09	20	1.12E-08	85	2.59E-07	30	3.58E-08	1.60E-01	1.04E-07
5.48E-02	2.44E-11	1.42E-01	3.55E-07	14	2.15E-09	30	1.5E-08	90	4.51E-07	40	5.15E-08	1.76E-01	1.17E-07
5.67E-02	2.44E-11	1.48E-01	4.53E-07	16	1.86E-09	40	1.84E-08	92	5.96E-07	50	6.97E-08	1.92E-01	1.30E-07
6.21E-02	2.44E-11	1.53E-01	6.60E-07	18	1.57E-09	50	2.18E-08	**Pressed Clay Brick**		60	9.12E-08	2.08E-01	1.43E-07
5.48E-03	1.64E-08	1.59E-01	1.64E-06	20	1.34E-09	60	2.54E-08	0	0	70	1.17E-07	2.24E-01	1.57E-07
1.10E-02	2.45E-08	**Reinforced Concrete**		**Parge Coating**		70	2.92E-08	10	8.95E-09	80	1.50E-07	2.40E-01	1.72E-07
1.64E-02	3.13E-08	0.5	5.60E-10	10	2.64E-08	80	3.35E-08	20	1.63E-08	90	1.93E-07	2.56E-01	1.87E-07
2.19E-02	3.76E-08	10	3.65E-10	20	3.64E-08	90	3.86E-08	30	2.26E-08	100	2.54E-07	2.72E-01	2.03E-07

Table 6b. Liquid (Moisture) Diffusivity of Building Materials

Exterior Grade Gypsum Board (Contd.)		Exterior Grade Gypsum Board (Contd.)		Fiber Cement Board		Fiber Cement Board (Contd.)		Fiber Cement Board (Contd.)	
Moisture Content, $kg \cdot kg^{-1}$	Diffusivity, $m^2 \cdot s^{-1}$	Moisture Content, $kg \cdot kg^{-1}$	Diffusivity, $m^2 \cdot s^{-1}$	Moisture Content, $kg \cdot kg^{-1}$	Diffusivity, $m^2 \cdot s^{-1}$	Moisture Content, $kg \cdot kg^{-1}$	Diffusivity, $m^2 \cdot s^{-1}$	Moisture Content, $kg \cdot kg^{-1}$	Diffusivity, $m^2 \cdot s^{-1}$
2.88E-01	2.188E-07	5.28E-01	6.276E-07	10	3.47E-09	160	1.63E-09	310	4.27E-09
3.04E-01	2.357E-07	5.44E-01	6.905E-07	20	1.87E-09	170	1.68E-09	320	5.35E-09
3.20E-01	2.534E-07	5.60E-01	7.346E-07	30	1.62E-09	180	1.72E-09	330	7.61E-09
3.36E-01	2.718E-07	5.76E-01	6.373E-07	40	1.53E-09	190	1.78E-09	340	1.67E-08
3.52E-01	2.910E-07	5.92E-01	4.219E-07	50	1.48E-09	200	1.84E-09		
3.68E-01	3.111E-07	6.08E-01	2.795E-07	60	1.46E-09	210	1.90E-09		
3.84E-01	3.322E-07	6.24E-01	2.048E-07	70	1.45E-09	220	1.98E-09		
4.00E-01	3.545E-07	6.40E-01	1.633E-07	80	1.45E-09	230	2.07E-09		
4.16E-01	3.780E-07	6.56E-01	1.386E-07	90	1.46E-09	240	2.18E-09		
4.32E-01	4.031E-07	6.72E-01	1.231E-07	100	1.47E-09	250	2.31E-09		
4.48E-01	4.302E-07	6.88E-01	1.135E-07	110	1.49E-09	260	2.46E-09		
4.64E-01	4.597E-07	7.04E-01	1.080E-07	120	1.51E-09	270	2.65E-09		
4.80E-01	4.926E-07	7.20E-01	1.058E-07	130	1.54E-09	280	2.89E-09		
4.96E-01	5.300E-07	7.36E-01	1.07E-07	140	1.57E-09	290	3.2E-09		
5.12E-01	5.742E-07			150	1.6E-09	300	3.63E-09		

Table 7. Air Permeability of Building Materials

Material	Air Permeability, $kg \cdot m^{-1} \cdot s^{-1} \cdot Pa^{-1}$
Granite veneer	Impermeable (Not measurable)
Nepean sandstone	$(5.9 \pm 1.0) \times 10^{-10}$
EIFS base and finish coats	Impermeable (Not measurable)
Terra cotta clay tile	$(1.6 \pm 0.8) \times 10^{-10}$
Reinforced concrete	$(2.0 \pm 0.2) \times 10^{-11}$
St. canut stone (sandstone)	$(1.9 \pm 0.5) \times 10^{-10}$
Parge coating	$(1.9 \pm 0.3) \times 10^{-09}$
Type 'O' mortar	$(7.3 \pm 2.6) \times 10^{-10}$
Tyndall limestone	$(3.5 \pm 3.7) \times 10^{-10}$
Pressed clay brick	$(1.8 \pm 0.3) \times 10^{-10}$
Type 'K' mortar	$(1.3 \pm 0.5) \times 10^{-07}$
Exterior grade gypsum board	$(5.90 \pm 0.17) \times 10^{-9}$
Fibre cement board	$(1.7 \pm 3.2) \times 10^{-9}$
Self adhesive membrane, A	Impermeable (Not measurable)
Self adhesive membrane, B	Impermeable (Not measurable)
Self adhesive membrane, C	Impermeable (Not measurable)
Torch applied asphalt based membrane	Impermeable (Not measurable)
Aged polyethylene film	Impermeable (Not measurable
High density mineral fiber insulation	$(2.4 \pm 0.1) \times 10^{-05}$
High density glass fiber insulation,	$(4.1 \pm 0.8) \times 10^{-05}$
Foil faced polyisocyanurate,	Impermeable (Not measurable)
Paper faced polyisocyanurate,	Impermeable (Not measurable)
Cellulose fibre insulation	2.9×10^{-04} (approximately)

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