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Heat, Air and Moisture Transport Properties of Three North American Stuccos

ABSTRACT: Heat, air, and moisture transfer models that are used as practical building design tools require reliable inputs to provide meaningful results. One of these inputs is the set of heat, air, and moisture transport properties of materials. For any given class of building materials the properties may vary within a broad range. This paper reports the porosity, density, matrix density, thermal conductivity, equilibrium moisture content, water vapor permeability, water absorption coefficient, liquid diffusivity, and air permeability of regular lime stucco, regular Portland cement stucco, and acrylic stucco that are commonly used in North America. The experimental and analytical procedures follow either international standards or well-established methodologies.

KEYWORDS: stucco, porosity, density, matrix density, thermal conductivity, equilibrium moisture content, water vapor permeability, water absorption coefficient, liquid diffusivity, air permeability.

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Building researchers active in the field of heat, air, and moisture transfer analyses have developed many computer models in recent years [1,2]. All these models require a very reliable set of inputs to yield meaningful results. Among these inputs are included the properties of the building materials. The most commonly used properties today are those from an International Energy Agency Annex [3]. As building materials evolve there is a need for continuous updating of 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 [4,5]. One of these projects [5] specifically looked at the ranges of the properties shown by contemporary products in North America. As reported earlier [6], the products chosen for that investigation included wood and wood-based materials, bricks, mortar, stucco, and building membranes. This paper reports the properties of three types of stuccos that are currently used in North America.

The properties that have been measured include:

1. porosity, density, and matrix density as basic material characteristics
2. thermal conductivity
3. equilibrium moisture content
4. water vapor permeability
5. water absorption coefficient
6. moisture diffusivity and
7. air permeability

Materials

The three types of stuccos used in this investigation are all commercial products and they can be identified as:

Stucco 1: Regular lime stucco

Stucco 2: Regular Portland cement stucco

Stucco 3: Acrylic stucco

Large (approximately 40 cm X 60 cm X 15 mm) slabs of the stuccos were cast and allowed to cure for 28 days before test specimens were prepared for various tests. The casting was done side by side with the preparation of several full-scale (2.4 m X 2.4 m) stucco walls that were subjected to rain penetration tests in a parallel project at the Institute. The stucco mixes and applications complied with the requirements in Section 9.28 of the National Building Code of Canada. The regular lime stucco mix consisted of one part by volume of Portland cement, one half part by volume of lime, and 4.5 to 5.5 parts by volume of aggregate. Regular Portland cement stucco mix consisted of one part by volume of Portland cement, one part by volume of masonry cement, and 4.5 to 5.5 parts by volume of aggregate. The acrylic stucco mix was a fiber-reinforced plaster pre-mix with an acrylic finish.

Basic Principles of Experimental Procedures

Basic Material Characteristics

The basic material characteristics- density, open porosity, and matrix density- were all determined following a procedure used in a recently concluded European Union project called HAMSTAD [7]. The open porosity Ψ_o of a porous material sample is defined as the ratio of the volume of the open pores to the total volume of the sample. The bulk density ρ is defined as the ratio of the dry mass of the sample to its volume, while the matrix density ρ_{mat} is defined as the ratio of the dry mass to the volume of the solid matrix, including closed pores.

The necessary data are obtained from a vacuum saturation test. Each test specimen is first dried in an oven to remove the majority of the physically bound water and then placed in an airtight container. During at least 3 h the air in the container is evacuated with a vacuum pump. De-aired water is then supplied to the container, at a low inflow rate. Once the sample is immersed, the water supply is cut and the specimen is kept under water for 24 h. In the course of the test the absolute air pressure in the container shall not exceed 2000 Pa. From the mass of the dry sample, m_d, the mass of the water-saturated sample m_w, and the mass of the immersed water-saturated sample (Archimedes weight) m_a, the volume V of the sample can be determined:

$$V = \frac{m_w - m_a}{\rho_l} \qquad (1)$$

with ρ_l being the density of liquid water. The basic hygric properties of the sample are then given by:

$$w_{sat} = \Psi_o \rho_l = \frac{m_w - m_d}{V} \qquad (2)$$

$$\rho = \frac{m_d}{V} \qquad (3)$$

$$\rho_{mat} = \frac{m_d}{V(1-\Psi_o)} \qquad (4)$$

Thermal Conductivity of Dry Materials

The heat conduction equation is used directly to determine the thermal conductivity λ 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. ASTM Standard Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded-Hot-Plate Apparatus (C 177) [8] and, ASTM Standard Test Method for Steady-State HeatFflux Measurements and Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus (C 518) [9] are widely used for this purpose. The latter is used in the present investigation. Similar standards are available from the International Standards Organization and the European Union. In the ASTM Standards, the heat conduction equation is written for practical applications as:

$$\lambda = Q \cdot l/(A \cdot \Delta T) \tag{5}$$

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 Eq (5) is called apparent thermal conductivity. It is a function of the mean temperature of the test specimen.

Equilibrium Moisture Content from Sorption/Desorption Measurements

For sorption measurements, the test specimen is dried at an appropriate drying temperature to constant mass. While maintaining a constant temperature, the dried specimen is placed consecutively in a series of test environments, with relative humidity increasing in stages, until equilibrium is reached in each environment. Equilibrium in each environment is confirmed by periodically weighing the specimen until constant mass is reached. From the measured mass changes, the equilibrium moisture content at each test condition can be calculated and the adsorption isotherm drawn.

The starting point for the desorption measurements is from an equilibrium condition very near 100% RH. While maintaining a constant temperature, the specimen is placed consecutively in a series of test environments, with relative humidity decreasing in stages, until equilibrium is reached in each environment. Equilibrium in each environment is confirmed by periodically weighing the specimen until constant mass is reached. Finally, the specimen is dried at the appropriate temperature to constant mass. From the measured mass changes, the equilibrium moisture content at each test condition can be calculated and the desorption isotherm drawn. ASTM Standard Test Method for Hygroscopic Sorption Isotherms of Building Materials (C 1498) [10] gives further details of the procedure.

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:

$$\ln\varphi = -\frac{M}{\rho RT} p_{\mathrm{h}} \qquad (6)$$

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 [11] briefly describes a procedure for pressure plate measurements and reports the results from an interlaboratory comparison. No standard procedure is yet developed for the determination of the suction isotherm.

Water Vapor Permeability/Permeance

The vapor diffusion equation is used directly to determine the water vapor permeability, δ_p of building materials. 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 determined gravimetrically. From these data the water vapor permeability of the material is calculated as:

$$\delta_p = J_v \cdot l/(A \cdot \Delta p) \qquad (7)$$

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

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

$$\delta_l = J_v/(A \cdot \Delta p) \tag{8}$$

ASTM Standard, Test Methods for Water Vapor Transmission of Materials (E 96) [12], prescribes two specific cases of this procedure- a dry cup method that gives the permeance or permeability at a mean RH of 25 % and a wet cup method that gives the permeance or permeability at a mean RH of 75 %. A new CEN Standard 89 N 336 E is being developed in the European Union based on ISO standard 12572:2001. More recently a number of technical papers that deal with various technical aspects, limitations, and analyses of the experimental data of these procedures have appeared in the literature [13-16].

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.

A new CEN Standard 89 N 370 E on the determination of the water absorption coefficient gives further details on the experimental procedure and data analysis.

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:

$$J_l = - \rho_0 D_w \text{ grad } u \tag{9}$$

Where,

ρ_0 = density of the dry material

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 [17] is used as the experimental technique. The data are analyzed using the Boltzmann transformation [18, 19] 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 [20-22].

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 differentials across the specimen are recorded. From these data the air permeability, k_a is calculated as:

$$k_a = J_a \cdot l/(A \cdot \Delta p) \qquad (10)$$

Where,

J_a = Air flow rate across an area A

l = Thickness of the specimen

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:

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

ASTM Standard, Standard Test Method for Airflow Resistance of Acoustical Materials (C 522) [23] prescribes a method based on this principle. Bomberg and Kumaran [24] have extended the method for general application to building materials.

Heat, Air, and Moisture Transfer Properties of Stuccos

Basic Material Characteristics

The results from the vacuum saturation measurements are listed in Table 1. The Table also includes approximate dimensions of the test specimens and the standard deviations of each derived property. The laboratory temperature during these measurements was 21± 0.5 ℃.

TABLE 1: Basic material characteristics of three stuccos: Vacuum saturated water content, W_{sat}, Porosity, ψ_0, density, ρ and matrix density, ρ_{mat}.

Stucco No	Dimension, mm X mm X mm	Number of Specimens	W_{sat}, kg m^{-3}	ψ_0, m^3 m^{-3}	ρ, kg m^{-3}	ρ_{mat}, kg m^{-3}
1	40 X 40 X 12	9	234 ± 5	0.234 ± 0.005	1943 ± 11	2538 ± 16
2	40 X 40 X 14	9	206 ± 4	0.206 ± 0.004	2087 ± 13	2629 ± 12
3	40 X 40 X 12	9	259 ± 7	0.259 ± 0.007	1926 ± 18	2599 ± 5

Thermal conductivity at two mean specimen temperatures

Two 30 cm X 30 cm test specimens of each type of stucco were precision-cut for uniform thickness from the cured slabs and were monolithic. 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 %). The results from these measurements are listed in Table 2.

TABLE 2. Thermal conductivities λ of three stuccos at two mean temperatures, T_{mean}.

Stucco	Specimen Thickness, mm	T_{mean}, °C	λ, W m^{-1} K^{-1}
Stucco 1	14.3	0.37	0.348
	14.3	22.4	0.366
	12.7	0.30	0.320
	12.7	20.3	0.338
Stucco 2	14.7	0.24	0.389
	14.7	22.5	0.406
	12.9	0.20	0.390
	12.9	22.3	0.409
Stucco 3	11.9	0.44	0.345
	11.9	22.2	0.363
	13.8	0.13	0.376
	13.8	22.6	0.400

From the above measured values it is estimated that for all three products the temperature coefficient of thermal conductivity is approximately 9 X 10^{-4} W m^{-1} K^{-2}.

Equilibrium moisture content

50 mm X 50 mm X 6 mm specimens were used in establishing the equilibrium moisture contents. 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) – constant relative hum idity chambers (controlled within 0.5 %) were used for the sorption/ desorption measurements. The suction measurements were performed at laboratory conditions, 21± 0.5 °C. The results fr om these measurements are listed in Table 3.

The pressure plate measurements were performed with new materials. The starting point was vacuum saturation. In the section on basic material characteristics, the vacuum saturation was repeated after more than two years and with samples that were aged in the laboratory for that period. It can be seen that there are some differences in the two sets of saturation moisture contents determined in these two series of measurements.

TABLE 3. Equilibrium moisture contents of three stuccos at various relative humidities, RH.

RH, %	Moisture content, kg kg^{-1}		
	Stucco 1	Stucco 2	Stucco 3
100 (saturation)	0.160± 0.003	0.120± 0.003	0.160± 0.004
99.93 (suction)	0.157± 0.003	0.117± 0.001	0.157± 0.004
95 (desorption)	0.090± 0.003*	0.072± 0.004*	0.055± 0.004*
90(desorption)	0.084± 0.001	0.070± 0.002	0.069± 0.002
70(desorption)	0.062± 0.002	0.052± 0.001	0.051± 0.002
50(desorption)	0.050± 0.001	0.042± 0.001	0.043± 0.002
50(sorption)	0.040± 0.004	0.030± 0.002	0.016± 0.002
70 (sorption)	0.052± 0.002	0.037± 0.001	0.041± 0.002
90 (sorption)	0.074± 0.002	0.058± 0.002	0.054± 0.002

* *specimens were prepared from a sample that was aged in the lab for more than two years; this ageing seems to have made some differences in the equilibrium moisture contents measured at 95 % RH.*

Water absorption coefficient

Four test specimens, 50 mm X 50 mm X 12 mm, were used for each material in these measurements. For all specimens, the major surfaces were parallel to the faces of the stucco slabs 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.

TABLE 4. Water absorption coefficients, *A* of three stuccos.

Stucco	*A* kg m^{-2} $s^{-½}$
Stucco 1	0.0051 ± 0.0001
Stucco 2	0.0123 ± 0.0003
Stucco 3*	0.0074 ± 0.0002

***** *the surface with the acrylic finish was in contact with water for these measurements.*

Water vapor permeability

Six circular specimens, approximately 15 cm in diameter and 13 mm thick for stucco 1, 13.5 mm thick for stucco 2, and 10.5 mm for stucco 3 were used for these tests. All measurements were done at 23 ± 0.3°C. Three specimens of each 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 [14]. The results are listed in Tables 5. Though each measurement on each test specimen yielded test data with less than 1 % uncertainty, the gross uncertainty in the derived values may be as high as 30 %, according to the statistical package TableCurve, used for the analyses. The inhomogenity of the products is the main reason for this rather large uncertainty in the derived values.

TABLE 5. The dependence of water vapor permeability, δ_p of the stuccos on RH.

RH, %	δ_p, kg m^{-1} s^{-1} Pa^{-1}		
	Stucco 1	Stucco 2	Stucco 3
10	6.70E-13	5.85E-13	2.40E-12
20	1.34E-12	8.85E-13	2.55E-12
30	2.01E-12	1.19E-12	2.72E-12
40	2.68E-12	1.49E-12	2.90E-12
50	3.35E-12	1.80E-12	3.09E-12
60	4.02E-12	2.10E-12	3.29E-12
70	4.69E-12	2.41E-12	3.50E-12
80	5.36E-12	2.72E-12	3.73E-12
90	6.03E-12	3.03E-12	3.97E-12
100	6.70E-12	3.34E-12	4.23E-12

Liquid (moisture) diffusivity

The rectangular test specimens used for the gamma-ray measurements were approximately 20 cm X 6.5 cm X 1 cm. The specimens were cut with their major surfaces parallel to the major surface of each stucco slab. The liquid water uptake was parallel to the major surfaces and hence parallel to the major surfaces of the slabs.

Information on saturation water content from Table 3 and on water absorption coefficient from Table 4 allows one to estimate an average liquid diffusivity [25] perpendicular to the major surfaces of the stucco slabs. The values are listed in Table 6.

TABLE 6. Average liquid diffusivities, D_w, of three stucco (perpendicular to the face of the slab).

Stucco	D_w, $m^2\ s^{-1}$
Stucco 1	2.7 E-10
Stucco 2	2.4 E-09
Stucco 3	6.0 E-09

The results from the gamma-ray measurements that show the dependence of D_w on local moisture content are listed in Table 7. For stuccos 1 and 2 no analyzable data were available at the upper range of moisture concentrations.

TABLE 7. Dependences of liquid diffusivities (parallel to the face of the slab) of three stuccos on moisture concentration.

Moisture Concentration, $kg\ m^{-3}$	Liquid diffusivity, $m^2\ s^{-1}$		
	Stucco 1	Stucco 2	Stucco 3
20	1.12E-09	6.86E-10	
30	8.33E-10	5.40E-10	
40	7.44E-10	5.41E-10	4.54E-09
50	7.70E-10	6.62E-10	2.68E-09
60	9.22E-10	1.02E-09	1.89E-09
70	1.31E-09	2.15E-09	1.59E-09
80	2.33E-09	8.90E-09	1.51E-09
90			1.53E-09
100			1.58E-09
110			1.61E-09
120			1.62E-09
130			1.64E-09
140			1.68E-09
150			1.80E-09
160			2.04E-09
170			2.46E-09
180			3.14E-09
190			4.16E-09
200			5.57E-09
210			7.33E-09
220			9.26E-09

Air permeability

The test specimens (three for each material) used in these measurements were identical to those used for the water vapor permeability measurements. Pressure differences up to 3 kPa did not yield any measurable airflow rates for any of the specimens. The chambers that carried the test specimens [24] were pressurized to about 100 kPa and from the pressure decay rates the air permeabilities were estimated. The uncertainties in these estimations can be as high as 80 %. All measurements were done at 21 ± 0.5°C. The results are listed in Table 8.

TABLE 8. Air permeabilities, k_a, of three stuccos

Stucco	k_a, kg m^{-1} Pa^{-1} s^{-1}
Stucco 1	4.9 E-12
Stucco 2	8.5 E-12
Stucco 3	3.0 E-11

Concluding Remarks

Though the three stuccos are distinguished by calling them respectively regular lime stucco, regular Portland cement stucco, and acrylic stucco, the hygrothermal properties of all three generally fall within a rather short range. The only difference seems to be in the water absorption coefficient, which in turn is reflected in the moisture diffusivity. The water absorption coefficient of Portland cement stucco is five times higher than that for the lime stucco. The differences in the air permeabilities, though apparently large for all three products are insensitive to airflow across them and do not affect the results from hygrothermal analyses. The three products represent the stuccos in the current North American market. Therefore, for any hygrothermal analysis the properties reported here could be regarded as a representative set of properties for contemporary products.

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