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Heat, Air and Moisture Transport Properties of Several North American Bricks and Mortar Mixes

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ABSTRACT: Hygrothermal models are emerging as practical building design tools. These models require a set of reliable inputs to provide results that are meaningful to the designers. 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 six types of bricks and four mortar mixes that are commonly used in North America. The experimental and analytical procedures follow either international standards or well-established methodologies.

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

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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 [1,2]. All these models require a very reliable set of 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 [3]. 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 [4,5]. One of these projects [5] was specifically looking at the ranges of the properties shown by contemporary products in North America. The products chosen for that investigation included wood and wood based materials, bricks, mortar, stucco and building membranes. This paper reports the properties of six types of bricks and four types of mortars 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 six types of bricks used in this investigation are all commercial products and they can be identified as:

Brick 1: White concrete brick
Brick 2: Red matt clay brick
Brick 3: Buff matt clay brick
Brick 4: Textured coated clay brick
Brick 5: Concrete brick and
Brick 6: Calcium silicate brick

The four types of mortar mixes used in this investigation are as shown in Table 1.

TABLE 1: Mortar mixes used for the determination of hygrothermal properties.

Mix Formulation	Mortar Type	Parts by Volume		
		Portland Cement	Hydrated Lime	Aggregate
Portland Cement-Lime Mortar	S (Coded 1-S)	1	½	3½ to 4½
	N (Coded 1-N)	1	1	4½ to 6
		Masonry Cement Type S	Masonry Cement Type N	Aggregate
Masonry Cement Mortar	S (Coded 2-S)	1	0	2¼ to 3
	N (Coded 2-N)	0	1	2¼ to 3

30 cm X 30 cm slabs of the mortars were cast and allowed cure before test specimens were prepared.

Experimental Procedure

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 [6]. 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 three hours the air in the container is evacuated with a vacuum pump. De-aired water was 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:

$$V = \frac{m_w - m_a}{\rho_l} \tag{1}$$

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

$$w_{sat} = \Psi_o \rho_l = \frac{m_w - m_d}{V} \tag{2}$$

$$\rho = \frac{m_d}{V} \tag{3}$$

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

Thermal Conductivity of Dry Materials

The heat conduction equation is directly used 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 Standards, Standard Test Method for Steady-State Heat flux Measurements and Thermal Transmission Properties by Means of the Guarded-Hot-Plate Apparatus (C 177) [7] and, Standard Test Method for Steady-State Heat flux Measurements and Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus (C 518) [8], 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 (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 (C1498) [9] 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:

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

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 [10] 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 suction isotherm.

Water Vapor Permeability/Permeance

The vapor diffusion equation is directly used 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 RH's as constant boundary conditions), is gravimetrically determined. From these data the water vapor permeability of the material is calculated as:

$$\delta_p = J_v \cdot l/(A \cdot \Delta p) \tag{7}$$

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) [11], 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 [12-15].

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 water absorption coefficient is under development.

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 [16] is used as the experimental technique. The data are analyzed using the Boltzmann transformation [17, 18] 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 [19-21].

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:

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

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) [22] prescribes a method based on this principle. Bomberg and Kumaran [23] have extended the method for general application to building materials.

Hygrothermal Properties of Bricks and Mortar Mixes

Basic Material Characteristics

The results from the vacuum saturation measurements are listed in Tables 2 and 3. The Tables also include the dimensions of the test specimens and the standard deviations of each derived property. The laboratory temperature during these measurements was (21± 0.5) °C.

TABLE 2: Basic material characteristics of six bricks: Vacuum saturated water content, W_{sat}, Porosity, ψ_0, density, ρ and matrix density, ρ_{mat}.

Brick No	Dimension, mm X mm X mm	No. Of Specimens	W_{sat}, kg m^{-3}	ψ_0, m^3 m^{-3}	ρ, kg m^{-3}	ρ_{mat}, kg m^{-3}
1	70 X 70 X 12	12	109 ± 5	0.109 ± 0.005	2420 ± 13	2715 ± 2
2	71 X 56 X 12	8	231 ± 8	0.232 ± 0.008	2024 ± 11	2635 ± 12
3	71 X 58 X 12	8	364 ± 3	0.364 ± 0.003	1788 ± 7	2816 ± 6
4	71 X 58 X 12	8	316 ± 10	0.316 ± 0.010	1869 ± 15	2733 ± 19
5	71 X 58 X 12	8	104 ± 8	0.105 ± 0.008	2427 ± 25	2711 ± 13
6	80 X 80 X 12	8	239 ± 3	0.240 ± 0.003	2062 ± 8	2712 ± 2

TABLE 3: Basic material characteristics of four mortar mixes: Vacuum saturated water content, W_{sat}, Porosity, ψ_0, density, ρ and matrix density, ρ_{mat}.

Mortar	Dimension, mm X mm X mm	No. Of Specimens	W_{sat}, kg m^{-3}	ψ_0, m^3 m^{-3}	ρ, kg m^{-3}	ρ_{mat}, kg m^{-3}
1-S	80 X 80 X 20	9	300 ± 6	0.300 ± 0.006	1857 ± 19	2652 ± 13
1-N	80 X 80 X 19	9	310 ± 1	0.310 ± 0.001	1872 ± 9	2714 ± 10
2-S	80 X 80 X 19	9	420 ± 4	0.421 ± 0.004	1581 ± 12	2728 ± 3
2-N	80 X 80 X 19	9	387 ± 13	0.387 ± 0.013	1675 ± 35	2733 ± 2

Thermal conductivity at two mean specimen temperatures

The 30 cm X 30 cm test specimens of each type of brick were assembled from several precision-cut and friction-fitted slices with same thickness. The major surfaces of the slices were parallel to the face of the brick (surfaces that are usually exposed to weather conditions in construction). The mortar test specimens (30 cm X 30 cm) were precision-cut 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 Tables 4 and 5.

TABLE 4. Thermal conductivities, λ of six bricks at two mean temperatures, T_{mean}.

Brick	Specimen Thickness, mm	T_{mean}, °C	λ, W m^{-1} K^{-1}
Brick 1	12.0	10.0	0.789
	12.0	22.5	0.792
Brick 2	12.4	10.8	0.489
	12.4	24.1	0.500
Brick 3	12.3	9.82	0.425
	12.3	24.2	0.434
Brick 4	12.3	9.82	0.509
	12.3	23.4	0.522
Brick 5	12.2	11.2	0.728
	12.2	24.0	0.737
Brick 6	12.2	10.5	0.614
	12.2	23.6	0.623

TABLE 5. Thermal conductivities, λ of four mortar mixes at two mean temperatures, T_{mean}.

Mortar mix	Specimen Thickness, mm	T_{mean}, °C	λ, W m^{-1} K^{-1}
1-S	19.6	-0.35	0.503
	19.6	23.0	0.527
	18.7	-1.19	0.501
	18.7	22.0	0.519
1-N	18.8	-1.02	0.381
	18.8	22.3	0.395
	19.1	-1.32	0.465
	19.1	20.5	0.482
2-S	19.1	0.03	0.435
	19.1	21.4	0.450
	18.6	-0.77	0.429
	18.6	21.7	0.446
2-N	18.7	-1.01	0.448
	18.7	22.1	0.460
	19.0	-0.73	0.453
	19.0	22.4	0.476

From the above measured values it is estimated that for both types of products the temperature coefficient of thermal conductivity is approximately 7 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 ºC) – constant relative humidity chambers (controlled within 0.5 %) were used for the former measurements. The latter were performed at laboratory conditions, (21± 0.5) ºC. The results from these measurements are listed in Tables 6 and 7.

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. The sorption and desorption undergone by the bricks in the hygroscopic region is rather small and measured mass changes are often within the precision range of the balance.

TABLE 6. Equilibrium moisture contents of six bricks at various relative humidities, RH.

RH, %	Measurement	Moisture Content, $kg\ kg^{-1}$					
		Brick 1	Brick 2	Brick 3	Brick 4	Brick 5	Brick 6
100	Suction	0.0534 ± 0.0036	0.112 ± 0.005	0.204 ± 0.002	0.177 ± 0.005	0.056 ± 0.006	0.140 ± 0.004
99.78	Suction	0.0535 ± 0.0031	0.112 ± 0.005	0.097 ± 0.014	0.057 ± 0.001	0.055 ± 0.005	0.104 ± 0.001
95.3	Suction	0.031 ± 0.001	0.029 ± 0.001	0.0039 ± 0.0000	0.049 ± 0.005	0.028 ± 0.002	0.073 ± 0.001
96.4	Desorption	0.031 ± 0.001	0.020 ± 0.001	0.023 ± 0.003	0.0225 ± 0.003	0.032 ± 0.003	0.048 ± 0.005
92	Desorption	0.030 ± 0.001	0.0007 ± 0.0000	0.0017 ± 0.0001	0.0016 ± 0.0000	0.022 ± 0.002	0.047 ± 0.0002
70	Desorption	0.0244 ± 0.0001	0.0006 ± 0.0001	0.000 ± 0.000	0.0006 ± 0.0000	0.0205 ± 0.0001	0.0330 ± 0.0003
50	Desorption	0.0207 ± 0.0001	0.0006 ± 0.0000	0.0020 ± 0.0000	0.0001 ± 0.0000	0.0147 ± 0.0001	0.0287 ± 0.0003
50	Sorption	0.0204 ± 0.0004	0.001 ± 0.0000	0.0012 ± 0.0003	0.0011 ± 0.0001	0.0148 ± 0.0003	0.0210 ± 0.0007
69	Sorption	0.0259 ± 0.0004	0.0011 ± 0.0000	0.0013 ± 0.0000	0.0005 ± 0.0000	0.0184 ± 0.0004	0.026 ± 0.001
91	Sorption	0.0300 ± 0.0000	0.0012 ± 0.0000	0.0012 ± 0.0000	0.0007 ± 0.0031	0.0264 ± 0.0001	0.047 ± 0.0003

Water absorption coefficient

Four test specimens, 50 mm X 50 mm X 12 mm were used for each material in these measurements. For all the bricks, the major surfaces of each specimen are parallel to the faces of the bricks 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 8.

TABLE 7. Equilibrium moisture contents of four mortar mixes at various relative humidities, RH.

RH, %	Measurement	MoistureContent, kg kg^{-1}			
		1-S	1-N	2-S	2-N
100	Suction	0.153 ± 0.001	0.158 ± 0.001	0.251 ± 0.003	0.264 ± 0.001
99.93	Suction	0.152 ± 0.002	0.158 ± 0.001	0.241 ± 0.008	0.254 ± 0.006
99.78	Suction	0.149 ± 0.002	0.157 ± 0.009	0.217 ± 0.018	0.205 ± 0.011
96.4	Desorption	0.089 ± 0.005	0.082 ± 0.006	0.074 ± 0.006	0.072 ± 0.005
90	Desorption	0.071 ± 0.001	0.077 ± 0.002	0.069 ± 0.001	0.061 ± 0.001
70	Desorption	0.060 ± 0.001	0.061 ± 0.001	0.054 ± 0.001	0.044 ± 0.001
50	Desorption	0.045 ± 0.001	0.047 ± 0.001	0.039 ± 0.001	0.034 ± 0.001
50	Sorption	0.026 ± 0.001	0.019 ± 0.001	0.005 ± 0.001	0.004 ± 0.001
70	Sorption	0.051 ± 0.001	0.040 ± 0.001	0.026 ± 0.001	0.023 ± 0.001
90	Sorption	0.066 ± 0.001	0.063 ± 0.002	0.065 ± 0.001	0.053 ± 0.001

TABLE 8. Water absorption coefficients, A of six bricks and four mortar mixes.

Brick	A, kg m^{-2} s$^{-½}$	Mortar Mix	A, kg m^{-2} s$^{-½}$
Brick 1	0.0076 ± 0.0002	1-S	0.063 ± 0.002
Brick 2	0.0268 ± 0.0007	1-N	0.086 ± 0.002
Brick 3	0.0012 ± 0.0002	2-S	0.011 ± 0.001
Brick 4	0.032 ± 0.005	2-N	0.016 ± 0.001
Brick 5	0.0097 ± 0.0009		
Brick 6	0.0181 ± 0.0003		

Water vapor permeability

Six rectangular test specimens, approximately 19 cm X 19 cm X 12.5 mm were used in these measurements, for each type of brick. For all the bricks, the major surfaces of each specimen are parallel to the faces of the bricks and therefore the water vapor transport was perpendicular to those surfaces. Six circular specimens, 15 cm in diameter and approximately 12.5 mm thick were used for all four mortar mixes. 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 %, 70 % and 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 % and 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 9 and 10. Though each measurement on each test specimen may yield 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 9. The dependence of water vapor permeability, δ_p of six bricks on RH.

RH, %	δ_p, kg m^{-1} Pa^{-1} s^{-1}					
	Brick 1	Brick 2	Brick 3	Brick 4	Brick 5	Brick 6
10	1.23E-12	1.51E-12	7.09E-12	3.04E-12	1.14E-12	1.14E-12
20	1.35E-12	1.57E-12	7.34E-12	3.15E-12	1.37E-12	1.74E-12
30	1.47E-12	1.64E-12	7.59E-12	3.26E-12	1.65E-12	2.65E-12
40	1.60E-12	1.70E-12	7.86E-12	3.37E-12	2.00E-12	4.06E-12
50	1.75E-12	1.77E-12	8.13E-12	3.48E-12	2.40E-12	6.25E-12
60	1.91E-12	1.84E-12	8.41E-12	3.60E-12	2.89E-12	9.72E-12
70	2.09E-12	1.91E-12	8.71E-12	3.73E-12	3.51E-12	1.54E-11
80	2.28E-12	1.99E-12	9.02E-12	3.86E-12	4.21E-12	2.50E-11
90	2.49E-12	2.07E-12	9.34E-12	3.99E-12	4.96E-12	4.26E-11
100	2.72E-12	2.15E-12	9.67E-12	4.13E-12	6.14E-12	7.97E-11

TABLE 10. The dependence of water vapor permeability, δ of four mortar mixes on RH.

RH, %	δ_p, kg m^{-1} Pa^{-1} s^{-1}			
	1-S	1-N	2-S	2-N
10	6.52E-12	7.72E-12	1.41E-11	1.34E-11
20	7.29E-12	8.64E-12	1.57E-11	1.48E-11
30	8.16E-12	9.68E-12	1.76E-11	1.64E-11
40	9.15E-12	1.09E-11	1.97E-11	1.82E-11
50	1.03E-11	1.22E-11	2.21E-11	2.02E-11
60	1.15E-11	1.37E-11	2.48E-11	2.24E-11
70	1.30E-11	1.55E-11	2.8E-11	2.50E-11
80	1.46E-11	1.74E-11	3.17E-11	2.79E-11
90	1.64E-11	1.97E-11	3.6E-11	3.12E-11
100	1.86E-11	2.23E-11	4.1E-11	3.5E-11

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 brick specimens were cut with their major surfaces parallel to the face of the brick. The liquid water uptake was parallel to the major surfaces and hence parallel to the face of the brick and parallel to the major surfaces of the mortar slabs.

Information on saturation water content from Table 2 and 3 and on water absorption coefficient from Table 8 allows one to estimate an average liquid diffusivity [24] perpendicular to the face of the brick and the major surfaces of the mortar slabs. The values are listed in Table 11.

TABLE 11. Average liquid diffusivities, D_w, of six bricks (perpendicular to the face) and four mortar mixes (perpendicular to the face of the slab).

Brick	D_w, m^2 s^{-1}	Mortar Mix	D_w, m^2 s^{-1}
Brick 1	4.9 E-09	1-S	4.4 E-08
Brick 2	1.3 E-08	1-N	7.7 E-08
Brick 3	1.1 E-11	2-S	6.8 E-10
Brick 4	1.0E-08	2-N	1.7 E-09
Brick 5	8.6E-09		
Brick 6	5.7E-09		

The results from the gamma ray measurements are listed in Tables 12 and 13. The moisture distribution data on Brick 1 and Mortar mix 2-S were not analyzable to derive any meaningful results and are not included in the tables. In general, the high densities of the masonry materials posed some limitations on the gamma ray method.

TABLE 12. Dependences of liquid diffusivities of five bricks on moisture concentration.

Moisture Concentration, kg m^{-3}	Liquid diffusivity, m^2 s^{-1}				
	Brick 2	Brick 3	Brick 4	Brick 5	Brick 6
30	8.49E-09	4.97E-08	2.48E-08	1.08E-08	7.11E-09
40	1.21E-08	5.94E-08	2.70E-08	3.46E-08	6.92E-09
50	1.92E-08	1.11E-07	2.84E-08	1.45E-08	1.73E-08
60	6.93E-08	1.36E-07	2.92E-08	1.19E-08	5.69E-09
70	2.41E-08	6.55E-08	2.97E-08	1.29E-08	5.04E-09
80	1.99E-08	5.32E-08	3.00E-08	2.29E-08	5.63E-09
90	1.89E-08	4.96E-08	3.01E-08		8.37E-09
100	1.91E-08	4.97E-08	3.02E-08		1.93E-08
110	2.03E-08	5.25E-08	3.01E-08		6.41E-09
120	2.27E-08	5.87E-08	3.01E-08		4.40E-09
130	2.72E-08	7.10E-08	3.00E-08		3.71E-09
140	3.76E-08	1.01E-07	3.00E-08		3.42E-09
150	1.06E-07	2.53E-07	3.01E-08		3.34E-09
160	4.34E-08	1.27E-07	3.02E-08		3.41E-09
170	3.55E-08	6.93E-08	3.04E-08		3.66E-09
180	3.93E-08	5.19E-08	3.08E-08		4.15E-09
190	1.14E-07	4.35E-08	3.14E-08		5.21E-09
200	1.52E-08	3.86E-08	3.23E-08		8.24E-09
210	9.46E-09	3.56E-08	3.36E-08		2.09E-08
220		3.37E-08	3.55E-08		
230		3.26E-08	3.83E-08		
240		3.22E-08	4.26E-08		
250		3.23E-08	4.96E-08		

TABLE 13. Dependences of liquid diffusivities of three mortar mixes on moisture concentration.

Moisture Concentration, kg m^{-3}	Liquid diffusivity, m^2 s^{-1}		
	1-S	1-N	2-N
30	7.47E-09	4.71E-08	4.74E-09
40	1.03E-08	5.41E-08	3.53E-09
50	1.33E-08	6.01E-08	3.12E-09
60	1.66E-08	6.56E-08	2.93E-09
70	2.03E-08	7.06E-08	2.86E-09
80	2.48E-08	7.53E-08	2.84E-09
90	3.06E-08	7.98E-08	2.88E-09
100	4.09E-08	8.41E-08	2.96E-09
110	2.59E-08	8.84E-08	3.10E-09
120	1.32E-08	9.27E-08	3.33E-09
130	7.06E-09	9.70E-08	3.73E-09
140	5.35E-09	1.01E-07	4.52E-09
150	4.66E-09	1.06E-07	7.07E-09
160	4.43E-09	1.11E-07	5.19E-09
170	4.52E-09	1.16E-07	2.24E-09
180	4.95E-09	1.22E-07	1.61E-09
190	5.96E-09	1.28E-07	1.25E-09
200	8.47E-09	1.35E-07	9.00E-10
210	2.12E-08	1.43E-07	6.13E-10
220	2.16E-08	1.54E-07	4.29E-10
230	7.56E-09	1.66E-07	3.19E-10
240	3.81E-09	1.84E-07	
250	2.29E-09	2.09E-07	

Air permeability

The test specimens 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. So the chambers that carried the test specimens {23} were pressurized to about 100 kPa and from the pressure decay rates the air permeabilities were estimated. The results are listed in Table 14. The uncertainties in these estimations can be as high as 100 %. All measurements were done at (21 ± 0.5)°C.

TABLE 14. Air permeabilities, k_a, of six bricks and four mortar mixes

Brick	k_a, $\text{kg m}^{-1}\text{ Pa}^{-1}\text{ s}^{-1}$	Mortar Mix	k_a, $\text{kg m}^{-1}\text{ Pa}^{-1}\text{ s}^{-1}$
Brick 1	5.0 E-10	1-S	3.7 E-10
Brick 2	1.5 E-10	1-N	1.6 E-10
Brick 3	3.2 E-10	2-S	7.1 E-10
Brick 4	1.4 E-09	2-N	1.5 E-09
Brick 5	8.2 E-11		
Brick 6	5.7 E-09		

Concluding Remarks

The results reported here indicate that the properties of bricks and mortar mixes may vary within a rather large range, from product to product. The concrete and clay bricks have some of the properties, for example the water vapor permeability, within a rather narrow range. But the calcium silicate brick shows a completely different dependence of vapor permeability on relative humidity. Most of the properties of mortar mixes 1-S and 1-N are within a small rage. The same is true with mortar mixes 2-S and 2-N. However the differences between the properties of Type 1 and Type 2 mortar mixes are noticeable.

The range of properties shown here suggests to the user of a hygrothermal model to be careful about choosing properties of masonry materials from any standard tables that give material properties. To get meaningful results from the analyses, the properties of these materials, especially those of the bricks have to be determined using standard procedures. However, it is hoped that the information presented here will help the modeler to carry out parametric analyses and establish the sensitivity of the final results to variations in the hygrothermal properties of masonry materials.

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