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**A LOGICAL EXTENSION OF THE ASTM STANDARD E96 TO DETERMINE
THE DEPENDENCE OF WATER VAPOUR TRANSMISSION ON RELATIVE
HUMIDITY**

REFERENCE: Lackey, J. C., Marchand, R. G., and Kumaran, M. K., "A Logical Extension of the ASTM Standard E96 to Determine the Dependence of Water Vapour Transmission on Relative Humidity," Insulation Materials: Testing and Applications: Third Volume, ASTM STP 1320, R.S. Graves and R.R. Zarr, Eds., American Society for Testing and Materials, 1997.

ABSTRACT: It is well known that the water vapour transmission properties of hygroscopic building materials depend on the local relative humidities(rh). Traditionally, the ASTM Standard E96 specifies only two conditions of rh. The dry cup method in the standard corresponds to a mean rh of 25 % and the wet cup to 75 %. This information is not enough to describe the behaviour of the material through the entire range of rh. European standards have already proposed an extension of the existing standard to address this issue. ASTM standard should follow this change. A logical extension of the E96 standard to include the effect of rh on water vapour transmission properties has been proposed and is being discussed by one of the C16 Committee Task Groups.

This paper presents the application of the proposed extension to several common building materials. The details include the operating principles of a constant temperature-rh chamber and the effects on the test results, of the vapour resistance offered by still air inside the cup, the surface resistances and buoyancy. The experimental data were used to critically assess the above effects. The data as well as the analyses of the data are expected to provide guidance to refine the existing ASTM Standard.

KEYWORDS: water vapour transmission, permeability, permeance, relative humidity, building materials, still air, surface resistance, buoyancy

INTRODUCTION

Water vapour permeability is probably the most commonly used hygrothermal property that characterizes building materials. Almost all insulation material standards in North America refer to this property as a performance parameter[1]. The property stems from the water vapour transport equation:

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$$\dot{m}_v = -\delta_p \text{ grad } p_v \quad (1)$$

where,

$$\begin{aligned} \dot{m}_v &= \text{water vapour transmission rate, kg} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \\ \delta_p &= \text{water vapour permeability of the medium, kg} \cdot \text{m}^{-1} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1} \\ p_v &= \text{water vapour pressure, Pa.} \end{aligned}$$

The above equation is derived from the Fick's law, which states that the density of diffusion flow rate of any material at a given point in a medium is directly proportional to its concentration gradient at that point, at constant temperature. In building physics applications, the water vapour pressure being significantly lower than the atmospheric pressure, the water vapour is assumed to follow the ideal gas equation and hence the concentration is substituted by the vapour pressure in equation(1).

Traditionally, building physicists have used equation(1) directly to measure the water vapour permeabilities of building materials. There has been very little change in the principle of the experimental procedure during the past six decades. In 1963, Joy and Wilson[2] thus wrote: "The simplest and most widely used test of the rate of water vapor transmission is the dish or the cup method. The specimen is sealed to the mouth of an impermeable test dish containing water or a desiccant, and placed in a controlled atmosphere. Periodic weighing of the assembly determines when a steady rate of weight loss or gain is attained, and this final rate, continued long enough to ensure its validity, is the test result....". The ASTM had standardized two dish methods, as early as 1954; E96 for thin sheets and C355 for materials, such as those used in building construction, tested in a thickness greater than 3 mm. Currently, the ASTM Standard, Designation E96-95, Standard Test Methods for Water Vapor Transmission of Materials is followed in Canada and the US. A recently concluded round robin series of measurements[3] confirmed that eight out of the nine participants strictly followed the standard.

It is well known that the water vapour transmission properties of hygroscopic building materials depend on the local relative humidities (rh)[4-6]. However, the ASTM Standard E96 specifies only two conditions of rh. The dry cup method in the standard corresponds to a mean rh of 25 % and the wet cup to 75 %. With the advent of very sophisticated tools for hygrothermal analysis of building materials and components[7], this information is not enough to describe the behaviour of the materials through the entire range of rh. European draft standards[8] have already proposed an extension of the existing standard to address this issue. ASTM standard should follow this change. A logical extension of the E96 standard to include the effect of rh on water vapour transmission characteristics has been proposed to the C16 Committee and is being discussed by one of the Task Groups[9].

This paper presents experimental results for several common building materials, using the extended E96 procedure proposed to the ASTM C16 Committee. Though equation(1) is rather straight forward, several test parameters have to be considered during the data analysis. These parameters include:

1. resistance offered by the still air layer in the cup
2. surface resistances on the bounding surfaces of the test specimen
3. buoyancy and
4. edge masking[2]

The results from the present study are used to illustrate the effects of the first three parameters on the final result. The design of the cups avoided the use of edge masking.

MATERIALS AND METHOD

The building materials included in this investigation are listed in Table 1. In addition to those materials, to illustrate the effect of buoyancy, selected sets of experimental data on samples of two materials, a plastic film and an aluminum sheet, with very high resistance towards water vapour transmission are also included.

TABLE 1-- A list of building materials investigated in this work.

Material	Dry density kg·m ⁻³	Specimen thickness mm
medium density glass fiber (MDGF) insulation board	54 ± 6	25.6 ± 0.4
gypsum board	644 ± 4	12.30 ± 0.04
plywood sheathing	430 ± 20	12.3 ± 0.1
expanded polystyrene (EPS) insulation board	11.4 ± 0.2	23.2 ± 0.2
wood fibreboard	278 ± 2	11.6 ± 0.3
calcium silicate insulation board	228 ± 2	19.6 ± 0.1
perlite insulation board	245 ± 6	20.0 ± 0.1

The experimental procedure is identical to those prescribed in the ASTM Standard E96. However, to include the full range of rh, a variety of conditions were maintained in the constant temperature-humidity chamber as well as inside the cup. The conditions inside the cup were maintained constant by using either a desiccant (anhydrous calcium chloride), or a salt solution[10] or distilled water.

Two separate constant temperature-humidity chambers (1.5 m × 1.15 m × 1.7 m) were recently built at the Institute to undertake a series of systematic measurements of water vapour transmission characteristics of common building materials as a function of rh. A schematic representation of the chamber is shown in FIG. 1. It works on the first principles of psychrometry. Air is drawn from the chamber at a constant speed through a duct system. It is then loaded with water vapour by pushing over a reservoir of warm water (35 to 40 °C). The moist air is then passed over a series of cooling coils maintained at a predetermined constant temperature, to correspond to the desired dew point (and hence the desired moisture content) inside the chamber. The excess moisture is condensed away from the incoming air by the cooling coils. Next, the air saturated at the dew-point

is pre-heated approximately to the chamber temperature. A thermally insulated part of the duct system evenly distributes the moist air inside the chamber and the cycle continues. The walls of the chamber carry aluminum panels with uniformly distributed and controllable heating coils to maintain constant temperature. The continuous circulation of air generates an air velocity $\approx 0.2 \text{ m}\cdot\text{s}^{-1}$ inside the chamber.

FIG. 1-- A schematic of the constant temperature-humidity chamber used in the measurements.

The chamber has been used to generate and maintain various levels of rh ranging between 20 % and 96 %. Four randomly chosen examples (FIG. 2) illustrate the stability of the chamber during the measurements. It is believed that this level of stability of the chambers significantly adds to the reliability of the data presented here. As a guideline, the nominal values of the rh maintained in the chamber and the cup to include the full range of rh are listed in Table 2. Real measured values are used in all calculations.

DATA ANALYSIS

The data were analyzed as prescribed in the current ASTM Standard. A mathematical least squares regression analysis of the change in mass as a function of time was used to determine the rate of water vapour transmission at the steady state. However, in the current standard, the rate so calculated is assumed to correspond only to the

TABLE 2-- Nominal conditions in the chamber and the cup in various measurements: the temperature is always 23 °C.

Mean Relative Humidity, %	The content of the dish(cup)	Humidity in the test dish, %	Humidity in the chamber, %
15	Desiccant	0	30
25	Desiccant	0	50
35	Desiccant	0	70
36.25	Saturated aqueous potassium acetate solution	22.51	50
45	Desiccant	0	90
51.58	Saturated aqueous potassium carbonate solution	43.16	60
59.43	Saturated aqueous potassium iodide solution	68.86	50
65	distilled water	100	30
70.45	Saturated aqueous potassium bromide solution	80.89	60
75	distilled water	100	50
80	distilled water	100	60
85	distilled water	100	70
90	distilled water	100	80
95	distilled water	100	90

resistance offered by the test specimen. In fact, the experimental set-up imposes four vapour resistances[11] in series between the content of the cup (the desiccant, salt solution or distilled water) and the chamber. These are:

1. the resistance offered by the layer of still air in the cup,
2. the resistance offered by the surface of the specimen inside the cup
3. the resistance offered by the test specimen
4. the resistance offered by the surface of the specimen outside the cup

If the thickness of the still air layer is known, the corresponding vapour permeance and hence the resistance can be calculated using the following equation[12] for permeability.

$$\delta_a = \frac{2.306 \times 10^{-5} P_o}{R_v T P} \left(\frac{T}{273.15} \right)^{1.81} \quad (2)$$

where,

δ_a = the permeability of still air, $\text{kg} \cdot \text{m}^{-1} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$

T = the temperature, K

P = the ambient pressure, Pa

P_o = the standard atmospheric pressure, i.e. 101325 Pa and

R_v = the ideal gas constant for water, i.e. $461.5 \text{ J} \cdot \text{K}^{-1} \cdot \text{kg}^{-1}$.

In the absence of any measured data, the surface resistances may be approximated using Lewis' relation[13]. According to Hansen and Lund[11] for cup methods that follow the ASTM Standard, the total surface resistance should be $\approx 4 \times 10^7 \text{ Pa}\cdot\text{s}\cdot\text{m}^2\cdot\text{kg}^{-1}$.

FIG. 2-- Four randomly chosen examples to illustrate the long-term stability of the chambers, which contributes significantly to the reliability of the results; the temperature inside is monitored continuously using several thermocouples at various locations and the humidity using a calibrated chilled-mirror sensor.

Corrections are to be made for the resistances offered by the still air and the two surfaces for all cup measurements. However, for vapour tight materials (measured transmission rate of the order of $10^{-8} \text{ kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ or less) these corrections are within the limits of the experimental uncertainty. For example, for a specimen of plywood sheathing, the following results were obtained:

water vapour transmission rate	$= 2.58 \times 10^{-8} \text{ kg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$
permeance(uncorrected)	$= 5.52 \times 10^{-11} \text{ kg} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$
thickness of still air	$\approx 15 \text{ mm}$
permeance (corrected for still air layer)	$= 5.55 \times 10^{-11} \text{ kg} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$
total surface resistances[11]	$\approx 4 \times 10^7 \text{ Pa} \cdot \text{s} \cdot \text{m}^2 \cdot \text{kg}^{-1}$
permeance (corrected for still air layer and surface resistances)	$= 5.56 \times 10^{-11} \text{ kg} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$

On the other hand, for vapour permeable materials the corrections become significant and can not be neglected. For example, for a specimen of MDGF, the following results were obtained:

water vapour transmission rate	$= 2.27 \times 10^{-6} \text{ kg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$
permeance(uncorrected)	$= 3.85 \times 10^{-9} \text{ kg} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$
thickness of still air	$\approx 15 \text{ mm}$
permeance (corrected for still air layer)	$= 5.46 \times 10^{-9} \text{ kg} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$
total surface resistances[11]	$\approx 4 \times 10^7 \text{ Pa} \cdot \text{s} \cdot \text{m}^2 \cdot \text{kg}^{-1}$
permeance (corrected for still air layer and surface resistances)	$= 6.98 \times 10^{-9} \text{ kg} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$

Yet another type of correction that can not always be neglected is the buoyancy correction. The duration of one set of measurements can be many days or weeks. The atmospheric pressure may significantly change during such periods. If the test specimen is a highly vapour resistant one, the changes in mass due to the vapour transport may be overshadowed by the apparent gravimetric changes observed. In such cases at least, all gravimetric data should be corrected to those in vacuum (the intention is to bring all the measurements to the same base line; this may also be done by making the base line to correspond to standard atmospheric conditions). The following equation[14] can be used for such corrections:

$$\frac{m_2}{m_1} = 1 + \frac{\rho_a(\rho_1 - \rho_2)}{\rho_1(\rho_2 - \rho_a)} \quad (3)$$

where,

m_1	= weight recorded by the balance, kg
m_2	= mass corrected for buoyancy effect, kg
ρ_a	= density of air, $\text{kg} \cdot \text{m}^{-3}$
ρ_1	= density of the material of the balance weights, $\text{kg} \cdot \text{m}^{-3}$
ρ_2	= bulk density of the test assembly, $\text{kg} \cdot \text{m}^{-3}$

The density of air can be calculated using the ideal gas law for the measured atmospheric pressure and ambient temperature. The following two examples illustrate the effect of the buoyancy correction.

FIG. 3 shows the results from one set of measurements on a test specimen of a plastic film. The corrected data gave statistically a better fit to the straight line (linear correlation coefficient of 0.998 vs 0.992) and yielded a permeance value $= (4.50 \pm 0.03) \times$

$10^{-12} \text{ kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$ while the raw data yielded $(3.97 \pm 0.05) \times 10^{-12} \text{ kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$. The difference between the two are much larger than the standard errors. Furthermore, when the measurements were continued for approximately 1100 h, both the corrected and raw data gave a permeance value $= 4.7 \times 10^{-12} \text{ kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$, closer to the value estimated using the corrected data for the first 350 h.

FIG. 4 shows the results on an aluminum sheet. The measured changes in mass are one order of magnitude less than those in FIG. 3. The raw data initially did not make any sense. Apparently, the mass decreased first, then increased and then decreased again. But the corrected data indicated a very small but measurable (about 10 mg) increase in mass in 200 h. Ideally, the aluminum sheet should exhibit infinite resistance to vapour transport. The measurements, however, indicate the presence of physical phenomena, such as adsorption or diffusion through micro-cracks in the sheet or the assembly itself. This has provided the data to demonstrate the effect of ambient pressure on weighings.

FIG. 3-- The effect of buoyancy corrections on the test results on a highly vapour resistant material.

RESULTS

The results from several series of measurements on the materials in Table 1 are listed in Table 3. For each test condition, three test specimens were used and all values are listed. The temperature was always in the vicinity of 23°C (FIG. 2). The mean rh is calculated as the average of those in the cup and in the chamber. All four corrections listed in the section on data analysis were made on all measurements.

FIG. 4-- Experimental results on an aluminum sheet to illustrate the effect of buoyancy correction.

CONCLUSIONS

The extended ASTM E96 Standard test procedure has systematically generated a reliable set of data on the permeabilities of several common building materials as a function of rh. It is equally applicable to highly vapour permeable and vapour resistant materials. Indeed this procedure has been used by others[5] and also proposed in the draft of a European Standard[8].

The design of the experimental set-up makes the results susceptible to various types of errors mentioned in the section on data analysis. However, these errors can be corrected theoretically. No additional measurements appear to be necessary. The error introduced by the still air layer inside the cup should always be corrected. The equation(2) suggested by Schirmer[12] is quite adequate in this regard. For highly permeable materials, such as the MDGF used in this investigation, the resistance offered by the bounding surfaces of the test specimens can not be neglected. This should be $\approx 4 \times 10^7 \text{ Pa}\cdot\text{s}\cdot\text{m}^2\cdot\text{kg}^{-1}$. As these corrections are made, the measured permeability for MDGF in the vicinity of 100 % rh approaches that of still air (Table 3), as indicated by an earlier series of investigations[15-17].

The permeability of still air under the test conditions is $\approx 2 \times 10^{-10} \text{ kg}\cdot\text{m}^{-1}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$. This is the expected upper limit of water vapour permeability. As many parameters influence the final result, measurements done on highly permeable test specimens often can give unacceptable results that exceed the upper limit. It is gratifying to see that none of the

51 measurements on MDGF in this investigations resulted in a permeability value that is not acceptable. This adds to the reliability of the experimental procedure and results reported here.

TABLE 3-- Water vapour permeabilities of several common building materials; three values that correspond to three separate test specimens are listed at each test condition.

Material	Mean rh %	Water vapour permeability $\text{kg}\cdot\text{m}^{-1}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$	Mean rh %	Water vapour permeability $\text{kg}\cdot\text{m}^{-1}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$
MDGF	16.1	$(1.15;1.14;1.10) \times 10^{-10}$	66.0	$(1.22;1.20;1.19) \times 10^{-10}$
	17.5	$(0.83;0.78;0.82) \times 10^{-10}$	70.9	$(1.41;1.24;1.24) \times 10^{-10}$
	25.6	$(1.14;1.06;1.09) \times 10^{-10}$	71.0	$(1.51;1.60;1.45) \times 10^{-10}$
	26.1	$(0.95;0.97;0.96) \times 10^{-10}$	80.6	$(1.35;1.18;1.15) \times 10^{-10}$
	36.9	$(1.14;1.18;1.26) \times 10^{-10}$	81.2	$(1.40;1.52;1.57) \times 10^{-10}$
	37.8	$(0.99;1.00;0.97) \times 10^{-10}$	90.1	$(1.76;1.91;1.66) \times 10^{-10}$
	44.6	$(1.20;1.19;1.19) \times 10^{-10}$	90.4	$(1.30;1.23;1.42) \times 10^{-10}$
	51.7	$(0.55;0.57;0.57) \times 10^{-10}$	94.6	$(1.74;1.93;1.77) \times 10^{-10}$
gypsum board	61.0	$(1.89;1.91;1.66) \times 10^{-10}$		
	14.4	$(3.73;3.70;3.80) \times 10^{-11}$	71.4	$(4.71;5.14;4.82) \times 10^{-11}$
	25.5	$(3.06;3.45;3.38) \times 10^{-11}$	80.7	$(4.65;4.66;4.75) \times 10^{-11}$
	36.7	$(2.78;2.87;2.87) \times 10^{-11}$	90.2	$(6.25;5.84;6.70) \times 10^{-11}$
	52.4	$(2.68;2.61;2.73) \times 10^{-11}$	96.2	$(8.84;7.34;8.76) \times 10^{-11}$
plywood sheathing	60.0	$(4.22;4.03;4.50) \times 10^{-11}$		
	16.1	$(3.68;3.74;4.29) \times 10^{-13}$	71.0	$(1.35;1.22;0.88) \times 10^{-12}$
	25.6	$(4.02;4.61;4.80) \times 10^{-13}$	81.2	$(7.50;9.38;9.18) \times 10^{-12}$
	37.8	$(6.84;6.62;7.06) \times 10^{-13}$	90.1	$(1.39;1.51;1.19) \times 10^{-11}$
	51.7	$(9.24;9.74;9.50) \times 10^{-13}$	94.6	$(2.36;2.56;2.13) \times 10^{-11}$
EPS	61.0	$(6.80;7.97;7.76) \times 10^{-13}$		
	14.4	$(8.80;10.9;11.9) \times 10^{-12}$	71.4	$(9.38;11.7;12.6) \times 10^{-12}$
	25.5	$(7.24;8.97;9.79) \times 10^{-12}$	80.7	$(9.14;12.0;12.2) \times 10^{-12}$
	36.7	$(8.29;9.79;8.02) \times 10^{-12}$	90.2	$(1.02;1.19;1.19) \times 10^{-11}$
	52.4	$(6.66;8.23;7.01) \times 10^{-12}$	96.2	$(1.23;1.34;1.13) \times 10^{-11}$
	60.0	$(8.93;10.8;8.75) \times 10^{-12}$		

The effect of buoyancy becomes significant in tests on highly vapour resistant materials. In those cases the measured masses should be corrected for the fluctuations in atmospheric pressure. These measurements may take many weeks to yield analyzable results. Corrections made for the effect of buoyancy can considerably reduce the duration of the test.

TABLE 3(continued)-- Water vapour permeabilities of several common building materials; three values that correspond to three separate test specimens are listed at each test condition.

Material	Mean rh %	Water vapour permeability $\text{kg}\cdot\text{m}^{-1}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$	Mean rh %	Water vapour permeability $\text{kg}\cdot\text{m}^{-1}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$
wood fibreboard	16.4	$(3.23;2.81;2.75) \times 10^{-11}$	77.9	$(3.79;3.58;3.75) \times 10^{-11}$
	24.0	$(3.04;3.07;3.07) \times 10^{-11}$	87.0	$(4.55;3.91;3.97) \times 10^{-11}$
	36.8	$(2.75;2.70;2.83) \times 10^{-11}$	91.1	$(4.36;4.10;4.59) \times 10^{-11}$
	46.5	$(2.86;2.98;3.18) \times 10^{-11}$	96.9	$(4.27;4.87;6.13) \times 10^{-11}$
	66.3	$(3.42;3.28;3.11) \times 10^{-11}$		
calcium silicate	16.4	$(3.09;3.06;3.07) \times 10^{-11}$	77.9	$(4.86;4.79;4.90) \times 10^{-11}$
	23.5	$(3.79;3.62;3.65) \times 10^{-11}$	87.3	$(5.31;5.47;6.36) \times 10^{-11}$
	36.8	$(3.36;3.24;3.31) \times 10^{-11}$	91.1	$(6.51;6.45;6.97) \times 10^{-11}$
	47.0	$(3.74;3.61;3.71) \times 10^{-11}$	96.8	$(8.53;7.98;9.44) \times 10^{-11}$
	66.3	$(4.18;4.17;4.36) \times 10^{-11}$		
perlite	16.4	$(3.03;3.00;3.00) \times 10^{-11}$	77.9	$(3.83;3.58;3.68) \times 10^{-11}$
	23.5	$(3.69;3.55;3.42) \times 10^{-11}$	87.3	$(3.37;3.12;3.76) \times 10^{-11}$
	36.8	$(2.98;2.89;3.04) \times 10^{-11}$	91.1	$(3.72;3.33;3.30) \times 10^{-11}$
	47.0	$(3.17;3.13;3.07) \times 10^{-11}$	96.8	$(4.01;2.00;2.56) \times 10^{-11}$
	66.3	$(3.26;3.27;3.47) \times 10^{-11}$		

For the measurements on the MDGF all the 14 conditions listed in Table 2. were applied. Some of the results showed rather large deviations (FIG. 5). It was noticed that these corresponded to the use of the salt solutions in the cup. The same effect was seen in the measurements on the gypsum board, EPS and the plywood. Hence salt solutions were avoided in the measurements on the wood fibreboard, calcium silicate and perlite specimens. The results on these specimens exhibit much less deviations, as shown by the data on the wood fibreboard specimens (FIG. 5). Probably it is more practical to use only the desiccant and distilled water to generate the necessary rh conditions inside the cup. Salt solutions provide the rh based on the principle of lowering of vapour pressure of the solvent. Material purity and maintenance of the saturation conditions are very crucial in attaining the prescribed rh.

In cup methods, the mean rh is traditionally calculated as the average of the rh in the cup and in the chamber. This same procedure is followed in this work. Alternate methods have been suggested by other workers[18,19]. One such method is used to analyze the data on wood fibreboard in the Appendix. At a later stage ASTM task groups should consider these approaches.

FIG. 5-- Experimental data on MDGF and wood fibreboard test specimens.

The data in FIG. 5 show that the property called water vapour permeability is not deterministic. If enough measurements are done, the stochastic nature of the property emerges. Admittedly, the uncertainties introduced by the equipment used in the measurements are partly responsible for this. The major reason for this is, however, the material inhomogeneity. This is true with all hygrothermal properties of building materials. More advanced tools[20] used for hygrothermal analysis of building materials and components have already started using the stochastic concept[7]. This is the beginning of the probabilistic approach to predict the long-term performance of building materials and components.

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APPENDIX

ALTERNATIVE ANALYSIS OF THE DATA BASED ON A METHOD SUGGESTED BY BAZANT AND NAJJAR

References 18 and 19 have used the following approach attributed to Bazant and Najjar¹ to determine the dependence of the water vapour permeability of hygroscopic materials on rh. If the cup measurements are done on a test specimen by keeping the rh on one side constant and successively increasing that on the other side in several steps, the steady state water vapour transmission data from each such step can be used to calculate the permeability of the material as a function of the rh as follows:

1. Convert the water vapour transmission data into Kirchhoff Flow Potential by multiplying with the thickness of the test specimen.
2. Plot the Kirchhoff Flow Potential against the varying rh; if the measurements are accurate this should result in a continuous curve.
3. The slope (Δ Kirchhoff Flow Potential / Δ rh) multiplied by (100/ the saturation water vapour pressure) gives the water vapour permeability at any chosen rh; these permeabilities should also be corrected for the resistance offered by the still air layer and any surface resistances.

Though the present measurements were not intended for the above method, the applicability of the method can be illustrated by taking all the data on the wood fibreboard as an example. The nine sets of measurements can be divided into two subsets. In one subset the rh on one side of the specimen is kept constant at 0 (the desiccant) and that on the other side increased in the following sequence; 32.8 %, 47.9 %, 73.7 % and 93.0 %. In the second subset the rh on one side is held constant at 100 % (distilled water) and that on the other side increased in the following sequence; 32.6 %, 55.9 %, 73.9 %, 82.2 % and 93.6 %. The water vapour transmission data when converted into the Kirchhoff Flow Potential results in two separate curves as shown in FIG A1. The two curves demonstrate the internal consistency of the data from nine separate sets of measurements on one material. The first subset directly gives the information on the variation of the Kirchhoff Flow Potential from 0 to 90 % rh. The information from the second subset can be used to extend the incomplete curve from 90 % to 100 % as follows. What one looks for is the Kirchhoff Flow Potential when one side of the specimen is at 0 and the other on 100 %. This can be considered as the sum of two separate Kirchhoff Flow Potentials - one for 0 to, (say) 50 % and the second from 50 % to 100 %. In fact any intermediate rh can be used instead of 50 % in such a calculation. All such calculations from the data give a value of $(6.8 \pm 0.1) \times 10^{-8} \text{ kg m}^{-1} \text{ s}^{-1}$ at 100 %. This completes the curve from 0 to 100 %. Now step 3 listed above can be used to calculate the water vapour permeability of the wood fibreboard at 23 °C. The results are shown in FIG A2. For comparison, the data from Table 3 and a set of results from an independent analysis of the data by one of the reviewers of this paper are also plotted in Fig A2. There is very little difference between

¹ Bazant, Z. P. and Najjar, L. J., "Nonlinear Water Diffusion in Nonstaturated Concrete", *Mat. & Constr.*, Vol 5, No 25, 1972, pp 3-20.

the three sets of results. It appears then that the mean rh calculations as recommended by the ASTM Standard E 96 do not result in unacceptable errors.

FIG. A1-- The Kirchhoff Flow Potentials from two subsets of measurements.

Fig A2-- Water vapour permeability of the wood fibreboard from three separate sets of data analysis.