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Publisher's version / Version de l'éditeur:

Journal of Testing and Evaluation, 33, September 5, pp. 316-322, 2005-09-01

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NRCC-46873

A version of this document is published in / Une version de ce document se trouve dans :
Journal of Testing and Evaluation, v. 33, no. 5, Sept. 2005, pp. 316-322

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Use of the 'Modified Cup Method' to Determine Temperature Dependency of Water Vapor Transmission Properties of Building Materials

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Reference: Mukhopadhyaya, P., Kumaran, M. K., and Lackey, J., '**Use of the 'Modified Cup Method' to Determine Temperature Dependency of Water Vapor Transmission Properties of Building Materials**,' *Journal of Testing and Evaluation*, American Society for Testing and Materials, West Conshohocken, PA, 2004.

Abstract: This paper describes a 'modified cup method' and its application to investigate the effects of temperature on the water vapor transmission properties of building materials. 'Modified cup method' is a simple and versatile technique that allows the user to vary the temperature condition of the test without altering the relative humidity. Two commonly-used building materials considered in this study were fiberboard, and gypsum board. The five temperature levels under consideration were between 7°C and 43°C. The water vapor transmission properties were measured at 50 % average relative humidity. The results obtained from these tests are critically analyzed and reported in this paper. These results demonstrate that there is a steady exponential increase of water vapor transmission (WVT) rate, through both the materials tested, with temperature. However, water vapor permeability (WVP) through the materials shows no significant change due to the variation of temperature between 7 and 43°C. The general observations made in this study confirm that the 'modified cup method' could be used reliably to measure water vapor transmission properties of building materials. Detailed analysis of the test results also reaffirm the fact that, for fiberboard and gypsum board, at 50 % average relative humidity condition, the water vapor permeability is not dependent on the temperature condition.

Keywords: 'modified cup method', water vapor transmission, temperature dependency, water vapor permeability

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Introduction

Building envelopes in North America are exposed to an extreme temperature regime, ranging from +50°C to -50°C [1,2]. Properties that define heat and moisture transport through building materials may depend on the local temperature. This dependency must be well defined to allow practicing building physicists or engineers to design the moisture movement inside and across the building envelope appropriately and realistically.

Water vapor permeability (WVP) is one of the most commonly defined parameters to characterize the moisture transport through any building materials. The ASTM Standard Test Methods for Water Vapor Transmission of Materials (E 96) are available to determine the WVP of any building materials at a single specific temperature (normally at 23 or 32.2 or 37.8°C). This single value of WVP is used to characterize the material. Nevertheless in real life building envelopes are exposed to wide range of temperatures. However, very little information is currently available on the temperature dependence of WVP for the commonly-used building materials in North America. This is mainly because of the lack of controlled environments to conduct tests over a range of temperatures. A recently developed 'modified cup method' has made it easier to conduct such tests and for the first time this method has been used in this study at different temperature levels.

The influence of temperature on the WVP through building materials has been investigated in this study using primarily the 'modified cup method'. Two commonly used building materials considered in the study for this purpose are: (1) fiberboard (natural finish paraffin wax-impregnated fiberboard), and (2) gypsum board. The five temperatures under consideration are 7, 16, 23, 34, and 43°C. The observations, obtained from the 'modified cup method', have also been verified by carrying out a limited number of 'conventional cup method' tests prescribed in the ASTM Standard Test Methods for Water Vapor Transmission of Materials (E 96).

Research Background and Significance

The building envelopes in North America are exposed to severe weather fluctuation. The variation of temperature between +50°C and -50°C is a realistic possibility. Temperature is a major driving force for moisture movement and influences sorption characteristics of the both organic and inorganic building materials [3]. Quite naturally it is to be expected that temperature variations have distinct effects on the moisture management strategy of the building envelopes. Increase of temperature induces greater mobility in the water molecules in any form of moisture and it is widely accepted that water vapor transmission through any material is a function of temperature [4-7]. The following relation, derived from Fick’s law, expresses the water vapor transmission (*WVT*) rate through porous materials as a function of temperature (*T*) and relative humidity (*RH*):

$$WVT = \mu(RH, T)\frac{\partial P}{\partial X} \qquad (1)$$

where:
‘*P*’ is the water vapor pressure and ‘*x*’ is the distance.

As can be seen in Equation 1, the water vapor permeability (*WVP*) 'μ' is a function of relative humidity (*RH*) and temperature (*T*). The relationship between water vapor permeability and relative humidity is very well established [*3,5,8*]. For non-hygroscopic materials, water vapor permeability values show little or no change with the variation of relative humidity. However, for hygroscopic materials, the water vapor permeability of materials increases with the increase of relative humidity. Kumaran [*9*] has suggested a method to derive the water vapor permeability values within the relative humidity (RH) range between 0 and 100 % using conventional wet-cup and dry-cup test results (ASTM E 96). Currently many state-of-the art numerical tools used for moisture design of building envelopes [*10*] consider water vapor permeability as a function of relative humidity [*11*].

On the other hand, temperature dependency of water vapor permeability (WVP) has been of interest to researchers for quite some time [*3-6,12*]. However, the extent of this influence of temperature on the water vapor permeability is not well known for most building materials. Nevertheless, attempts have been made to explain the effects of temperature on the water vapor permeability of certain types of materials on the basis of activation energy, a concept developed from kinetic theory of chemical reactions [*4*] as follows.

$$\mu = \mu_0 e^{(-E/RT)} \tag{2}$$

where:
μ_0 = permeability for $T = \infty$
R = gas constant
E = activation energy
T = absolute temperature

Equation 2 clearly indicates that higher temperature results in greater activated moisture diffusion. Theoretically the concept of activation energy, as stated above, can be readily accommodated in the moisture design process, particularly in numerical modeling tools, that will take into account the effect of temperature on the water vapor permeability of building materials. However, this can be done only when adequate experimental results are available. Currently researchers from the Institute for Research in Construction (IRC) are looking at the possibility to incorporate temperature effects on the moisture (both liquid and vapor) transport properties of building materials into the moisture management strategy. As a part of it, recent studies at the IRC [*13*] established that higher surface temperature of the material causes higher liquid moisture diffusion into 'eastern white pine wood'. However, negligible or little effects were found on liquid moisture diffusion in the same study when the materials were 'red clay brick' or 'concrete'. The research results in the following sections present the effect of temperature on the water vapor transmission properties of two building materials.

Experimental Program

A newly-developed method, named the 'modified-cup-method', has been used in this study to measure water vapor transmission properties of fiberboard and gypsum board at five temperature levels between 7°C and 43°C.

Test Procedure - 'Modified Cup Method'

Currently the ASTM standard E 96 is widely used for the measurement of water vapor permeability of building materials. In this method it is necessary to control both temperature and relative humidity (RH) during the test. Though not impossible, it is time consuming and not easy to maintain a constant RH condition in the humidity chamber while the temperature is changed. If RH is not maintained at a constant level for different temperature levels, then effects of both RH and temperature variations are reflected on the water vapor permeability results. In order to avoid any such possibilities, the 'modified cup method' [*14*], that combines both wet and dry cup test methods as described in the ASTM standard E 96, has been used in this study. A schematic diagram of the modified cup is shown in Figure 1 and pictures of the test assembly are shown in Figure 2. The circular specimen is sealed with silicone rubber inside a circular cylinder of ≈145 mm. This container is placed between a cylindrical wet cup (with water) at the bottom and a similar dry cup (with calcium chloride as desiccant) at the top. The desiccant in the dry cup at the top is separated from the specimen through a highly permeable thin sheet of spunbonded polyolefin. The average nominal relative humidity inside the test assembly is considered to be 50 %. However, the real value of the relative humidity at any stage of the test could be slightly different depending on the test material and moisture content of the desiccant. The whole test setup is held in place by two aluminum plates bolted together. The joints between the cylinder holding the specimen, and the dry (top) and wet (bottom) cups are made air/vapor tight by placing a rubber ring at each joint. The whole setup is then placed in a controlled temperature chamber. The assembly is taken out of the chamber and separated at regular intervals to measure the weights of specimen, water and desiccant container separately every time. Care was taken to complete the weighing accurately and quickly in order to avoid moisture transfer during the process.

Specimens

Two widely used building envelope components, fiberboard and gypsum board, have been considered in this study. While fiberboard is normally used as sheathing board in wood frame walls, it can also be used in various other wall constructions. Numerical simulation based on the fundamentals of heat, air, and moisture transport mechanisms indicates that hygrothermal response of sheathing board material plays an important role to govern the drying and wetting characteristics of the wall assembly [*15*]. Gypsum board is mainly used as interior facing of the wall. The physical size and properties of the test specimens are shown in Table 1.

Test Conditions and Equipment

Five temperature levels considered in this study were 7.4, 16.1, 22.8, 33.7, and 43°C. Temperature levels below 22.8°C were maintained inside a cooling chamber. Similarly, temperature levels above 22.8°C were maintained inside an oven. The controlled temperature and relative humidity chamber developed for the ASTM standard E 96 test procedure was used to conduct the test at 22.8°C. Both the cooling chamber and heating chambers had the capability to maintain temperature within the specified set point ±0.1°C for an indefinite long period. The mechanical balance used for weighing the specimens and test assemblies satisfied the criteria specified in the ASTM standard E 96.

Analysis of Test Results

The test results were analyzed with the same basic principles used for the ASTM standard E 96, wet and dry cup test procedures. In addition the following corrections [*16,17*] were applied to the test results.

1. Corrections for resistance due to the still air layer, and
2. Corrections due to resistance offered by the specimen surface.

Water Vapor Transmission

The change of desiccant or water weight is plotted against the elapsed time. A straightline observation, involving at least six properly spaced points, indicates the establishment of steady state water vapor transmission process. The slope of this straightline is the rate of water vapor transmission (WVT). The test results obtained in this study, when plotted and curve fitted, show a very clear straight line with a '*R*-square' value 0.99 or higher.

The water vapor transmission (WVT) rate is thus calculated using the following equation.

$$WVT = \frac{G}{tA} = \frac{(G/t)}{A} \tag{3}$$

where,
G = weight change of desiccant or water (kg)
t = time (s)
G/t = slope of the straight line (kg/s)
A = test area, i.e., cup mouth area (m^2), and
WVT = rate of water vapor transmission ($kg/s{\cdot}m^2$).

Water Vapor Permeance

$$WVPR = \frac{WVT}{S(R_1 - R_2)} \tag{4}$$

where:

S = saturation vapor pressure at test temperature (Pa),
R_1 = relative humidity at the source expressed as a fraction (the test chamber for desiccant method; in the dish for water method),
R_2 = relative humidity at the vapor sink expressed as a fraction, and
$WVPR$ = water vapor permeance (kg/m^2·s·Pa)

Water Vapor Resistance

The water vapor resistance (WVR) of a building component is expressed as the reciprocal of the water vapor permeance (WVPR) of the same.

$$WVR = \frac{1}{WVPR} \tag{5}$$

where:
WVR = water vapor resistance (m^2·s·Pa/kg)

Resistance Due to Still Air Layer

If the thickness of the still air layer present between the desiccant and specimen or water and specimen is known, then the corresponding water vapor resistance can be calculated using the following equation of permeability, proposed by Schirmer [*18*].

$$\delta_a = \frac{2.306\text{x}10^{-5}\,\text{P}_\text{o}}{\text{R}_\text{v}\text{TP}}\left(\frac{T}{273.15}\right)^{1.81} \tag{6}$$

where:
δ_a = the permeability of still air (kg·m^{-1}·s^{-1}·Pa^{-1})
T = the temperature (K)
P = the ambient pressure (Pa)
P_o = the standard atmospheric pressure, i.e. 101325 Pa (760 mm of Hg), and
R_v = the ideal gas constant for water, i.e. 461.5 J·K^{-1}·kg^{-1}.

The resistance offered by still air,

$$AR = \frac{1}{\delta_a} \tag{7}$$

Resistance Due to Specimen Surface

The surface resistances (i.e. inside and outside surfaces of the specimen) have been approximated using Lewis' relation [*19*]. For the 'modified cup method', the total surface resistance offered by two surfaces [*20*] is judged to be approximately 4 x 10^7 Pa·s·m^2·kg^{-1}.

Water Vapor Permeability of the Material

Corrected WVR of the specimen = (WVR from Equation 5) - (resistance offered by still air (Equation 7) and specimen surfaces (i.e., 4 x 10^7 Pa·s·m^2·kg^{-1})), i.e.,

$$WVR_{corrected} = \frac{1}{WVPR} - \frac{1}{\delta_a} - S_R \tag{8}$$

where:

S_R = resistance offered by the specimen surface (Pa·s·m^2·kg^{-1})

Corrected WVPR of the specimen = 1/ (Corrected WVR of the specimen), i.e.,

$$WVPR_{corrected} = \frac{1}{WVR_{corrected}} \tag{9}$$

Corrected water vapor permeability (WVP) of the material (kg·m^{-1}·s^{-1}·Pa^{-1}) = (Corrected WVPR of the specimen) x (thickness of the specimen), i.e.,

$$WVP_{corrected} = WVPR_{corrected} \times d \tag{10}$$

where:

d = thickness of the specimen (m)

A sample calculation using the aforementioned test procedure is shown in Appendix I.

Results and Discussion

The test results were analyzed as described in the previous section. In the 'modified cup method', the water vapor transport property can be calculated in two ways. It can be derived either from the weight change of the desiccant cup (i.e. dry cup) or from the weight change of the water cup (i.e. wet cup). In this study, the results were analyzed using data obtained from both wet cup and dry cup observations (Tables 2 and 3). The discussions on these analyzed results are presented in the following paragraphs.

Wet Cup and Dry Cup Test Results

In the 'modified cup method', the water vapor transmission properties can be calculated separately from two sets of data. One way is from the data on weight change of the water (i.e. wet cup) with the time and the other is from the data on desiccant (i.e. dry cup) weight change with the time. If the measurements are carried out properly, then the water vapor transmission properties from these two sets of separate test data should be the same. More specifically, when steady state of water vapor transmission is reached the weight gained by the desiccant should be the same as the weight lost from the water cup. As shown in Figure 3, the typical plot of weight change versus time for gypsum board at 33°C shows that weight loss and gain by the water and desiccant, respectively, are equal. It can also be seen in Tables 2 and 3 that the water vapor transmission properties derived from wet and dry cup observations are almost the same. However, the average of dry and wet cup results are plotted and the corresponding values from the best-fitted curve (Tables 2 and 3) are used for the purpose of discussion in the following paragraphs.

Effect of Temperature on the Water Vapor Transmission Rate

The effects of temperature on the rate of water vapor transmission (WVT) are shown in Figures 4a and 4b, and in Tables 2 and 3, for fiberboard and gypsum board, respectively. As would be expected, higher temperature leads to higher rate of WVT. The relationship between WVT rate and temperature can be seen as exponential in nature. At higher temperatures, the change in WVT rate is much more rapid than at the lower temperature. However, while looking at this relationship one should remember (see Equation 3) that rate of WVT is a measure of mass transfer per unit area of specimen and this it does not reflect the intensity of prevalent driving force causing the water vapor transmission. The water vapor transfer coefficient that represents the water vapor transfer property under unit driving force through unit area is called 'water vapor permeability'.

Effect of Temperature on the Water Vapor Permeability

The temperature effects on water vapor permeability (WVP) of the materials are shown in Figures 5a and 5b and in Tables 2 and 3. The results clearly indicate that there is very little and no consistent pattern of change in WVP with temperature for both fiberboard and gypsum board. From the test results obtained in this study, between the temperature range 7°C and 43°C, at 50 % average relative humidity, the water vapor permeability appears to be independent of temperature conditions. This observation is very much in line with the conclusion made by other researchers [*4-7, 12*] in the past. However, it is to be noted that in this study a different test methodology (i.e. the 'modified cup method') was used where it was possible to change the temperature without influencing relative humidity. These observations clearly indicate that the simple and versatile 'modified cup method' can be used extensively to find out the effect of temperature on water vapor permeability of building materials. The authors are particularly interested to develop a database of temperature dependency of water vapor permeability that includes all kinds of building materials currently in use. Further investigation is in progress and will be reported in due course.

Comparison Between Conventional Cup and Modified Cup Results

The reliability of the observations made in this study is very much dependent on the quality of the results obtained from the newly introduced 'modified cup method'. Unlike the conventional cup method, as described in the ASTM standard E 96, there is no precision and bias statement developed yet for the 'modified cup method'. Hence, it is necessary to conduct a benchmarking exercise for the results obtained from the 'modified cup method'. Figure 6 shows the results obtained from the conventional cup method (see the value at 50 % RH) and the 'modified cup method' for the gypsum board at ≅ 23°C. These results compare very well with each other. These observations surely establish the reliability of the test data obtained from the 'modified cup method'.

Conclusions

The following conclusions can be drawn from this study, using the 'modified cup method', that investigated the effects of temperature on the water vapor transmission properties of the two commonly used building materials, i.e. fiberboard and gypsum board.

1. For the materials considered in this study, and based on the independent wet and dry cup measurement, it has been demonstrated that at an average 50% relative humidity the water vapor transmission properties obtained from the 'modified cup method' are as reliable as those obtained from the conventional cup method as described in the ASTM standard E 96. However, further experimental data are required to reinforce this conclusion.
2. Water vapor transmission rate through fiberboard and gypsum board increases exponentially with the temperature increment within the range between 7°C and 43°C. Hence, in any moisture analysis where water vapor transmission rate is the input parameter, one needs to be concerned about the temperature effect.
3. However, the water vapor permeability of fiberboard and gypsum board does not alter with the temperature change within the range between 7 and 43°C when the average service relative humidity is around 50 %. Therefore, for such circumstances, in any moisture analysis where water vapor permeability is the input parameter, for these two materials, one needs not to be concerned about the temperature effect. Similar conclusions were arrived in reference 8 using conventional cup method.
4. It is hoped that the simple and inexpensive 'modified cup method' will encourage researchers around the world to generate more information on the temperature dependency of water vapor transmission characteristics of common building materials.

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Appendix I - Sample calculation:

Material - Fiberboard; Thickness = 11.45 mm
Test temperature = 22.82°C
Water vapor transmission (*WVT*) rate (Equation 3) = 5.58×10^{-3} g/m^2.s
Saturation vapor pressure at 22.82°C = 2779.66 Pa

Water vapor permeance (*WVPR*) (Equation 4) = $\frac{5.58\times10^{-6}}{2779.66}$ kg/m^2.s.Pa
= 2.00×10^{-9} kg/m^2.s.Pa

Water vapor resistance (*WVR*) (Equation 5) = $\frac{1}{2.00\times10^{-9}}$ m^2.s.Pa/kg
= 5.00×10^{8} m^2.s.Pa/kg

Total air layer thickness in the modified cup test assembly = 20 mm = 0.02 m
Ambient pressure (mm of Hg) = 745.04 Pa
Water vapor permeability of 20 mm still air (Equation 6)

$$= \frac{2.306\times10^{-5}\times760}{461.5\times295.97\times745.04}\left(\frac{295.97}{273.15}\right)^{1.81} \text{ kg/m.s.Pa} = 1.99\times10^{-10} \text{ kg/m.s.Pa}$$

Water vapor permeance of 20 mm still air = $\frac{1.99\times10^{-10}}{0.02}$ = 99.50×10^{-10} kg/m^2.s.Pa

Water vapor resistance of 20 mm still air = $\frac{1}{99.50\times10^{-10}}$ m^2.s.Pa/kg
= 1.01×10^{8} m^2.s.Pa/kg

Surface (two) resistance of the specimen = 4×10^{7} m^2.s.Pa/kg

Total resistance of air plus specimen surfaces = $(1.01 \times 10^{8} + 4 \times 10^{7})$ m^2.s.Pa/kg
= 1.41×10^{8} m^2.s.Pa/kg

True resistance of the specimen = Water vapor resistance - (resistance of air plus specimen surfaces)
= $(5.00 \times 10^{8} - 1.41 \times 10^{8})$ m^2.s.Pa/kg = 3.59×10^{8} m^2.s.Pa/kg

True water vapor permeance of the specimen = $\frac{1}{3.59\times10^{8}}$ kg/m^2.s.Pa
= 2.79×10^{-9} kg/m^2.s.Pa

True water vapor permeability of the material = True water vapor permeance of the specimen $\times$ thickness = $2.79 \times 10^{-9} \times 11.45 \times 10^{-3}$ kg/m.s.Pa = 3.19×10^{-11} kg/m.s.Pa

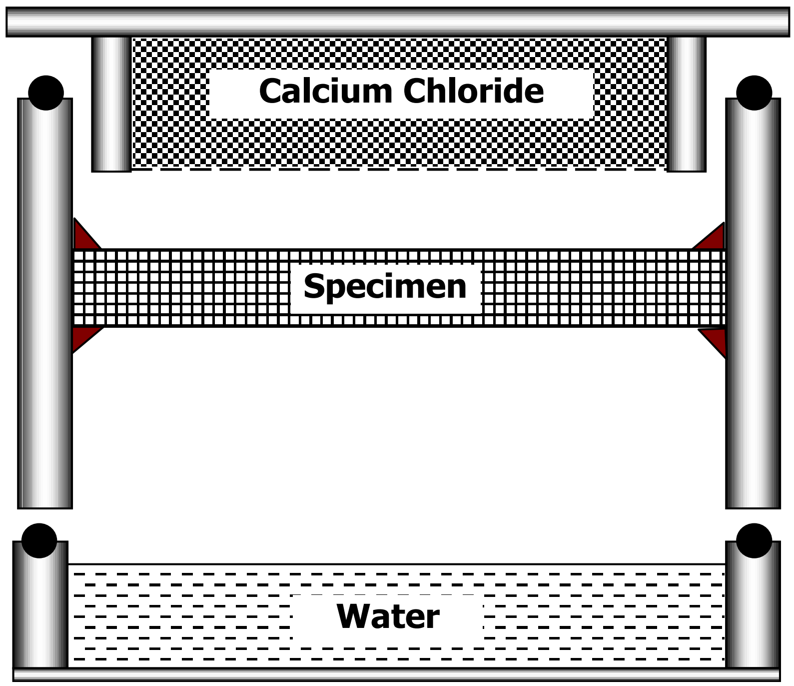

Figure 1- Schematic Diagram of Modified Cup Test Assembly

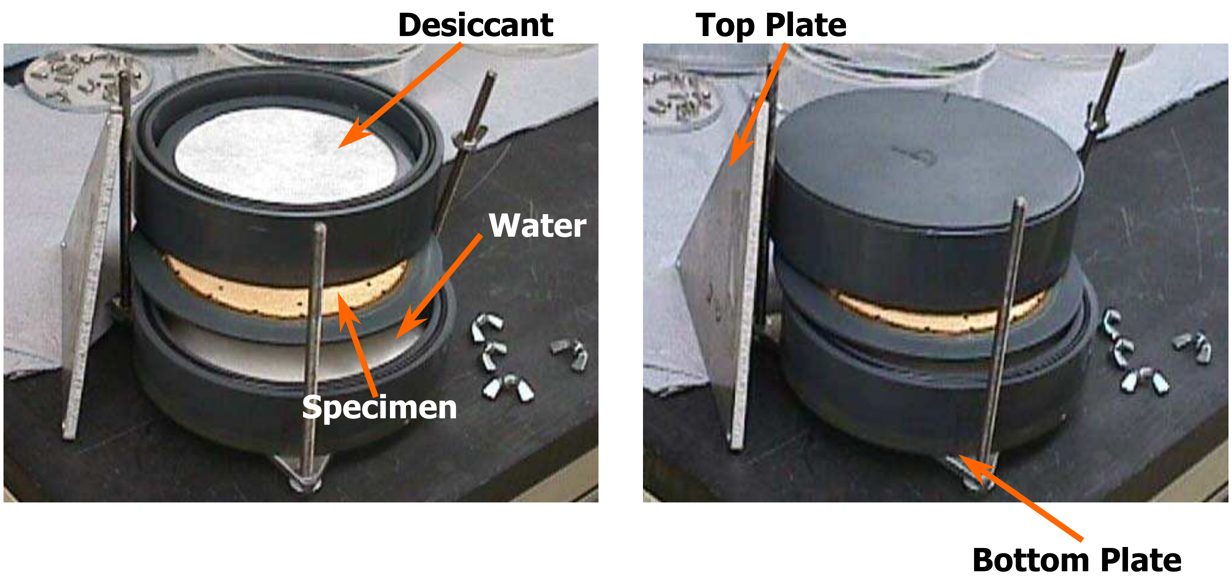

Figure 2 - Pictures of Modified Cup Test Assembly

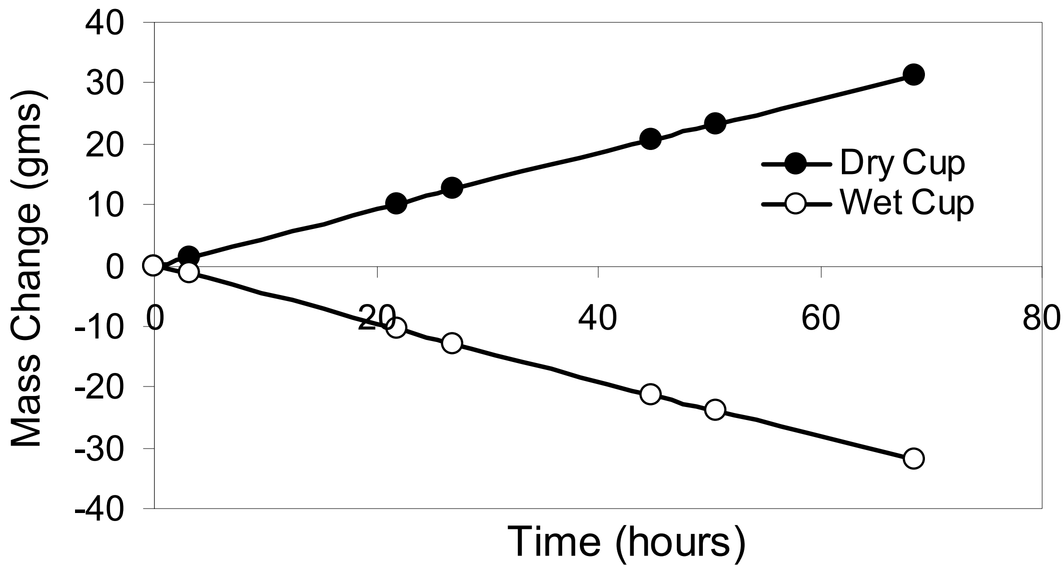

Figure 3 - Weight Gained by the Desiccant and Lost from the Water Cup (Gypsum Board, 33°C)

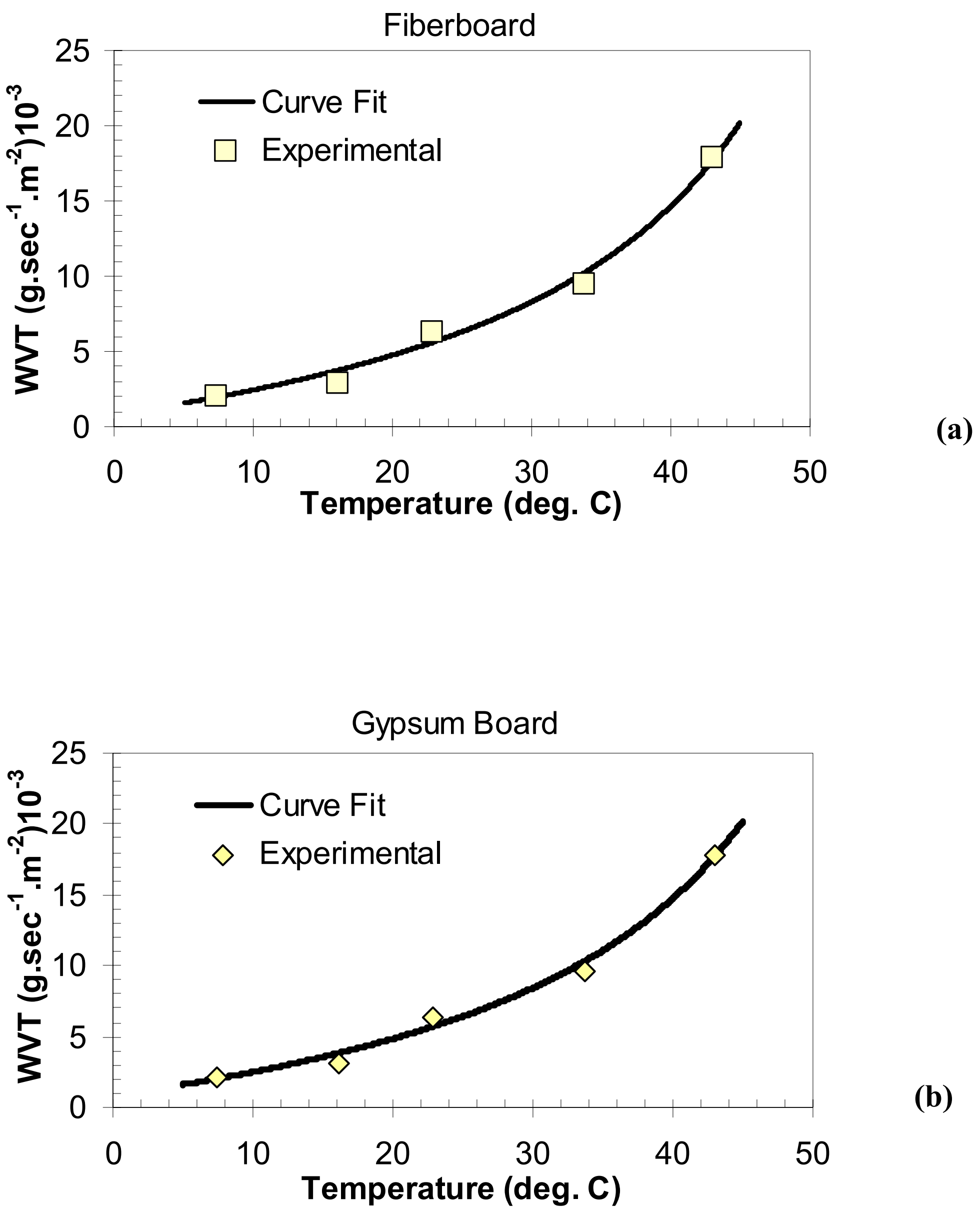

Figure 4 - Temperature Effects on Water Vapor Transmission (WVT) rate - (a) Fiberboard, and (b) Gypsum Board.

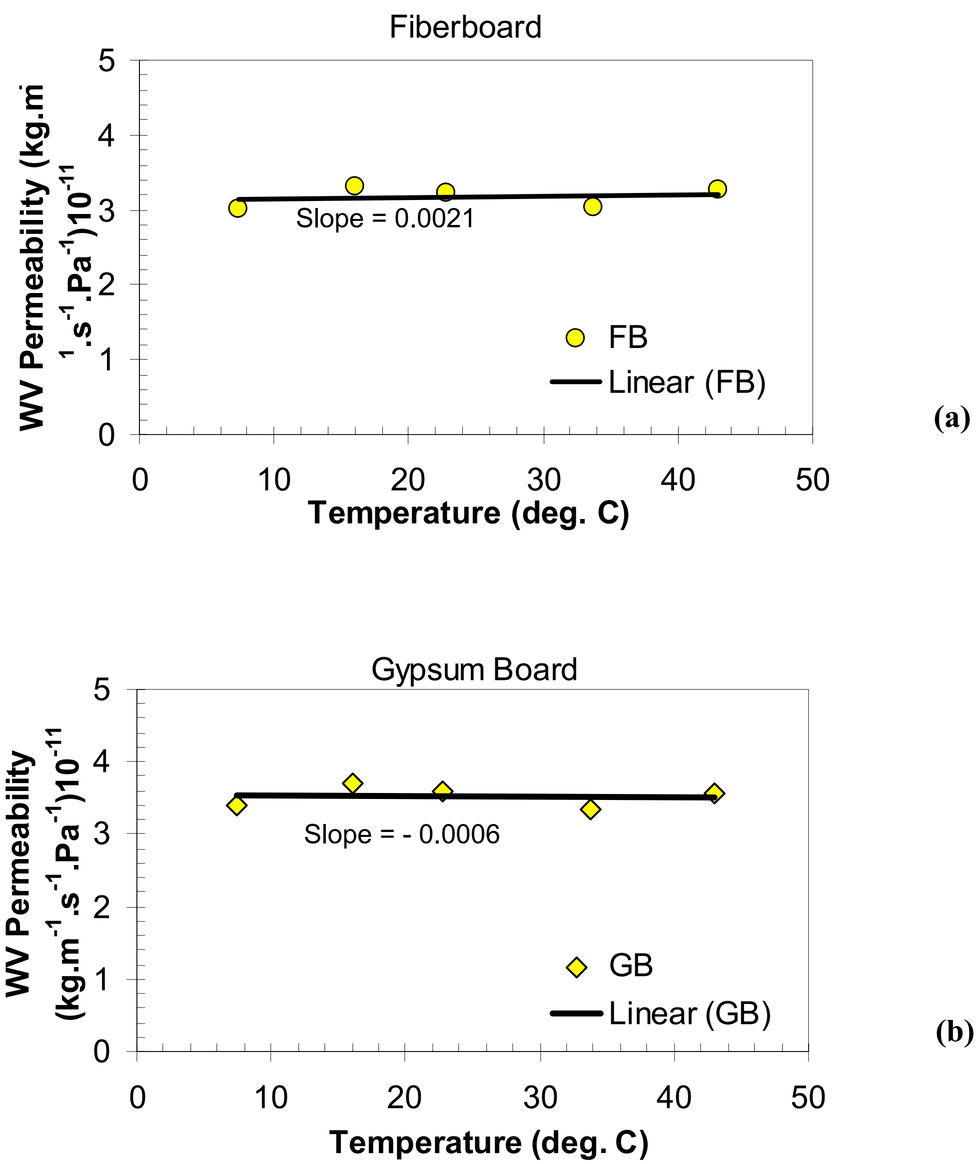

Figure 5 - Temperature Effects on Water Vapor Permeability (WVP) - (a) Fiberboard, and (b) Gypsum Board.

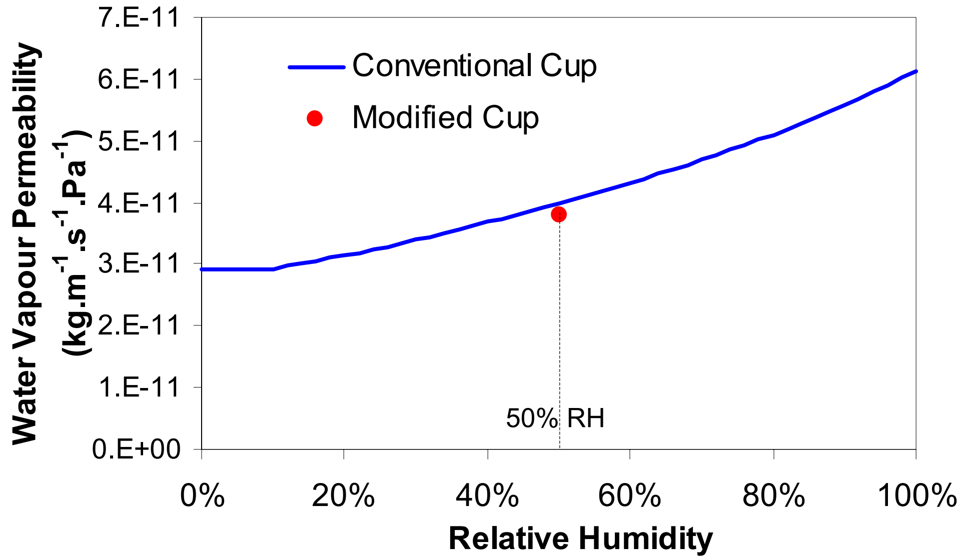

Figure 6 - Comparison Between Results - Conventional Cup and 'Modified Cup Method' (average relative humidity in the 'modified cup method' is 50%).

Table 1 - Physical Properties of Materials

Material	Diameter (cm)	Thickness (mm)	Density (kg/m^3)
Fiberboard	13.0	11.5	630
Gypsum Board	13.1	12.4	256

Table 2 - Water Vapor Transmission Properties of Fiberboard

Temp (°C)	Specimen	Fiberboard: Water vapor transmission rate (g/s.m^2).10^{-3} Wet cup	Mean	Dry cup	Mean	Mean of dry and wet cup	Values from the best fitted curve	Water vapor permeability (kg/m.s.Pa).10^{-11} Wet cup	Mean	Dry cup	Mean	Mean of dry and wet cup	Values from the best fitted curve
7.37	I	1.97	1.98	1.99	2.01	2.00	1.96	2.83	2.86	2.88	2.92	2.89	3.02
	II	2.00		2.04				2.89		2.97			
	III	1.98		2.01				2.86		2.92			
16.01	I	2.98	2.82	3.01	2.92	2.87	3.74	2.30	2.21	2.33	2.25	2.23	3.31
	II	2.90		2.93				2.23		2.26			
	III	2.77		2.82				2.11		2.15			
22.82	I	6.33	6.34	6.14	6.16	6.25	5.58	3.55	3.56	3.40	3.42	3.49	3.22
	II	6.37		6.23				3.59		3.48			
	III	6.31		6.10				3.54		3.38			
33.74	I	10.00	9.61	9.78	9.36	9.49	10.20	2.79	2.65	2.70	2.56	2.61	3.03
	II	9.58		9.30				2.63		2.54			
	III	9.25		9.00				2.52		2.43			
43.02	I	18.50	18.23	17.60	17.43	17.83	17.72	3.23	3.17	3.03	2.99	3.08	3.36
	II	18.20		17.50				3.17		3.00			
	III	18.00		17.20				3.11		2.94			

Table 3 - Water Vapor Transmission Properties of Gypsum Board

Temp (°C)	Specimen	Gypsum board											
		Water vapor transmission rate $(g/s.m^2).10^{-3}$						Water vapor permeability $(kg/m.s.Pa).10^{-11}$					
		Wet cup		Dry cup		Mean of dry and wet cup	Values from the best fitted curve	Wet cup		Dry cup		Mean of dry and wet cup	Values from the best fitted curve
			Mean		Mean				Mean		Mean		
7.37	I	1.98	2.08	2.06	2.07	2.08	2.01	3.10	3.31	3.28	3.32	3.32	3.40
	II	2.20		2.06				3.56		3.28			
	III	2.05		2.11				3.26		3.39			
16.01	I	3.07	3.08	3.11	3.13	3.11	3.83	2.60	2.61	2.64	2.66	2.64	3.71
	II	3.14		3.20				2.68		2.74			
	III	3.03		3.08				2.56		2.60			
22.82	I	6.36	6.41	6.20	6.25	6.33	5.69	3.88	3.92	3.74	3.79	3.86	3.59
	II	6.40		6.24				3.91		3.78			
	III	6.46		6.31				3.98		3.86			
33.74	I	9.68	9.75	9.65	9.58	9.67	10.33	2.90	2.92	2.89	2.86	2.89	3.35
	II	9.85		9.50				2.96		2.83			
	III	9.71		*				2.91		*			
43.02	I	18.30	18.23	17.50	17.50	17.87	17.76	3.47	3.46	3.27	3.28	3.37	3.56
	II	18.50		17.70				3.50		3.32			
	III	17.90		17.30				3.40		3.24			

*: Test data not recorded