Vapour barrier and moisture response of wood-frame stucco wall – results from hygrothermal simulation

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Vapour Barrier and Moisture Response of Wood-frame Stucco Wall –

Results from Hygrothermal Simulation

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ABSTRACT

This paper investigates the role of the vapour barrier in a wood-frame stucco wall with the help of two-dimensional hygrothermal simulation tool, *hygIRC-2D*, developed at the Institute for Research in Construction of the National Research Council Canada. For this purpose, the wall is subjected to the exterior weather conditions of Vancouver, Canada. Three different interior climatic conditions and seven different vapour diffusion strategies, generated by varying the water vapour permeance of the vapour barrier, installed outboard of the interior finish, have been considered in this study.

The outputs from the simulations have been analysed with the help of a novel moisture response indicator called RHT index. Simulation results indicate that the vapour permeance characteristics of the vapour barrier, in terms of water vapour permeance, plays a very important role in the overall moisture response of the wood-frame stucco wall. A very high or low vapour permeance of the vapour barrier does not produce the optimum moisture management strategy for the wood-frame stucco wall subjected to a climate as exists in Vancouver, Canada. Moreover, simulation results indicate that the removal of vapour barrier from the wall system can result in a heightened moisture response and a considerable accumulation of moisture in the interior gypsum board that may lead to severe consequences in particular, the premature deterioration of the interior facing board. It has also been observed from the simulation outputs that the optimum vapour diffusion strategy, that of limiting the vapour permeance of the vapour barrier, is not a function of interior climatic conditions considered in this study.

It is hoped that the results reported in this paper will shed some light on a number of concerns raised in recent years on the role of vapour barrier in wood-frame stucco wall construction.

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1.0 INTRODUCTION

The moisture design of exterior walls in a building envelope is becoming more complex in modern buildings. The functional variation, presence of different ventilation systems and use of new materials in construction have all contributed to this complexity. Without a proper vapour diffusion strategy, the short and long-term performance or durability of the wall can be seriously affected.

In absence of any air leakage, moisture in the form of water vapour diffuses through the wall assembly due to water vapour pressure and/or temperature gradient across the wall cross section. The direction of water vapour movement depends on the exterior climate and indoor environment. During the heating season (i.e. winter) almost all the time moisture moves toward the exterior face of the building envelope and during the cooling season (i.e. summer) most of the time moisture moves towards the inside of the building envelope. Condensation of this moisture inside the wall assembly is highly undesirable as it may lead to premature deterioration of the wall component on which it is deposited. Water vapour condensation takes place always in the part of the wall that is moist and cold. The role of the vapour barrier in the wall assembly is to control the moisture movement from the warmer part of the wall assembly to the colder part of the wall. For this precise reason, it is a requirement in the National Building Code of Canada (NBC, 1995) to install a vapour barrier protection on the warmer side of the insulation. However in real life the colder side of the insulation is not always static, particularly in geographical locations with fluctuating weather.

The role of the vapour barrier in building envelope construction is an issue that has been investigated and debated in Canada for over sixty years (Hutcheon, 1989; Swinton 1990). The complexity of the issue and the lack of definitive research mean, that for many smaller low-rise buildings, moisture diffusion continues to be governed by simple prescriptive requirements that are not particularly case-sensitive. Water vapour permeance for vapour barriers in these buildings, determined by ASTM E96 Procedure A, must not exceed 15 ng/(Pa.s.m^2) or 60 ng/(Pa.s.m^2) depending on the permeance of other materials in the assembly. For other buildings where professionals are expected to be involved in the design, the National Building Code of Canada (NBC) provides more general performance-based requirements that allow for greater case-sensitivity. Although there is no evidence of problems as a result of compliance with the NBC prescriptive requirements, questions remain regarding the specific limits prescribed. However, the exact influence of these prescriptive values on the overall moisture response of the wall due to climatic moisture load is still not very clear. Experimental data are needed to critically examine this issue but such experiments are time consuming, expensive and on occasions practically difficult to perform. In such a situation, the use of computer aided numerical modelling can be a realistic scientific option. However, this option is only useful if the model is benchmarked. The study undertaken in this paper uses a two-dimensional (2-D) modelling tool, *hygIRC-2D*, to assess the effect of vapour permeance characteristics of the vapour barrier on the overall moisture response of a wood-frame stucco wall exposed to various interior climatic conditions in Vancouver, Canada.

2.0 RESEARCH BACKGROUND

A two-dimensional numerical modeling study, carried out by Karagiozis and Kumaran (1993), questioned the necessity of specific water vapour permeance characteristics of the vapour barrier, as prescribed in the National Building Code of Canada (1990), installed at the interior side of the wall assembly in certain Canadian locations to achieve optimum moisture management. The results from this study indicated the necessity of location and specific water vapour permeance values for the vapour barrier. It was also suggested that it might not be necessary to install a vapour barrier for a wall built in Vancouver, Canada. However, these studies were done using constant interior boundary conditions (20°C and 38.5% relative humidity) and the presence of exterior cladding was not modelled. Moreover, the study neglected entirely the effect of driving rain, solar radiation and wind velocity on the water vapour movement through the wall assembly.

Further to the aforementioned study, Mukhopadhyaya et al. (2001) conducted a number of simulations for wood-frame stucco walls for locations of Ottawa and Vancouver, using a more advanced two dimensional modelling tool that takes into account the effect of driving rain, solar radiation, wind velocity and also the presence of exterior cladding. A single interior boundary condition was assumed to be variable and functionally related to the exterior climate. The results from this simulation study indicated that a vapour barrier having a higher water vapour permeance results in greater drying and wetting of the wall assembly in terms of total moisture content. This study did not look into the localized moisture response of the wall assembly.

The investigation reported in this paper analyses the localized response of the wood-frame stucco wall assembly, built with seven different vapour barrier systems and exposed to three different interior boundary conditions. The exterior climatic condition of Vancouver, Canada, is taken as the exterior boundary condition. A two dimensional (2-D) heat, air and moisture (hygrothermal) transport numerical simulation tool, *hygIRC-2D*, has been used for this study.

3.0 *hygIRC-2D* AND HYGROTHERMAL SIMULATION

The hygrothermal simulation tool used in this study is a computer aided numerical model, *hygIRC-2D*, that can predict the moisture response of building envelopes (Hens 1996). *hygIRC-2D* is continuously evolving as a research tool, developed by a group of researchers at the Institute for Research in Construction (IRC) of the National Research Council (NRC), Canada. Interested readers can refer to the publications by Karagiozis (1997) and Djebbar et al., (2002) for further details. These documents outline the formulation of the combined heat, air and moisture transport equations used in *hygIRC-2D* and the techniques used to solve them numerically. The reliability of *hygIRC-2D* outputs has been established through laboratory measurements and benchmarking exercises (*Maref et al. 2002*). The effective use of *hygIRC-2D* to analyse and obtain meaningful results, however, demands a proper physical understanding of the problem, an appropriate definition of input parameters and the ability to judiciously interpret the outputs from the simulation tool (Mukhopadhyaya and Kumaran, 2001; Mukhopadhyaya et al. 2001; and Mukhopadhyaya et al. 2002).

hygIRC-2D accommodates many advanced features, such as transient heat, air and moisture (liquid and vapour) transport, 2-dimensional spatial formulation, variable material properties with moisture content and temperature, air flow through building materials, wind driven rain penetration, effect of solar radiation, presence of moisture source inside the material, freeze-thaw effects, as well as many other useful features. To define the construction of the wall system, *hygIRC-2D* has a pre-processor that allows the user to divide a wall into a number of layers, in both the horizontal and vertical directions.

There are a number of major input parameters required for *hygIRC-2D* simulation, such as wall construction details, material properties, boundary conditions, exposure duration, initial moisture content and temperature.

The detailed descriptions of these parameters, as required for this study, are given in the following paragraphs.

3.1 Wall Construction Details

A wood-frame stucco wall has been considered in this study. The basic details of the construction of the wood-frame stucco wall are shown in Figure 1. The wall remains the same for all the simulations done in this study, and only the vapour permeance value of the vapour barrier is varied, as shown in Table 1, for the parametric study.

3.2 Material Properties for *hygIRC-2D*

hygIRC-2D simulation requires eight sets of material properties. These properties are air permeability, thermal conductivity, dry density, heat capacity, sorption characteristics, suction pressure, liquid diffusivity and water vapour permeability. These materials properties, for the wall construction shown in Figure 1, were obtained from the IRC/NRC's database and were determined in the IRC's Thermal and Moisture Performance Laboratory.

3.3 Boundary Conditions and Geographic Location

The outdoor climatic condition required for *hygIRC-2D* simulations has seven major weather components (i.e., temperature, relative humidity, wind velocity, wind direction, rain fall, solar radiation and cloud index) recorded on an hourly basis. In this study, the weather conditions for Vancouver (year 1969), representative of climatic conditions (i.e. average weather year) in the lower mainland of coastal British Columbia, Canada (i.e., temperate oceanic cool) is taken as exterior climate. The total exposure or simulation duration of two years (same weather year repeated) is used for the simulation.

The hourly indoor climatic condition (i.e., temperature, relative humidity) is considered here as a subject of parametric variation, details of which are described in section 4.0. Three different sets of data are used as shown in Table 1.

3.4 Initial Moisture Content

In this study, the initial moisture content of each wall component is assumed to be equivalent to the corresponding relative humidity of 50 percent, derived from the sorption isotherm of the respective materials.

4.0 PARAMETRIC VARIATION

The primary objective of this study is to find out the effect of different vapour permeance values of the vapour barrier on the overall long-term moisture response of the wood-frame stucco wall assembly exposed to different indoor boundary or climatic conditions. Hence, two parameters under investigation in this study are the variation of vapour permeance values of vapour barrier, installed outboard of the interior finish, and different climatic conditions as described in the following paragraphs.

4.1 Vapour Barrier

Seven cases of different vapour resistances, offered by vapour barrier and interior gypsum board, are considered in this study, as shown in Table 1 with the values of vapour permeance of vapour barrier and interior facing (i.e. gypsum board) together. The total vapour permeance values varied between 14.7 ng/m^2.s.Pa and 2753.3 ng/m^2.s.Pa.

4.2 Indoor Condition

Three different indoor conditions are considered in this study. These conditions include: (i) Constant 40% relative humidity (RH) and 22°C temperature (T) condition (Table 1), (ii) Controlled indoor condition (RH and T) according to ASHRAE Handbook of Fundamentals, Chapter 3 and criteria specified for winter and summer in "Specifications to the National (Canada) Energy Code for Houses" (Swinton & Sander, 1994) (Figure 2), and (iii) Indoor climatic conditions (Figure 3) that is derived from outdoor climatic data using the weather analysis tool *Weathersmart* (Djebbar et al. 2001) developed at the IRC/NRC. In this particular case, the indoor RH conditions have been derived using a model proposed by Jones (1995) with the indoor temperature 21°C (both for summer and winter), moisture load 7.5 litre/day, air leakage 1.44cm^2/m^2, volume 192m^3, air exchange rate (ACH) 0.3, and indoor maximum RH cap of 75%.

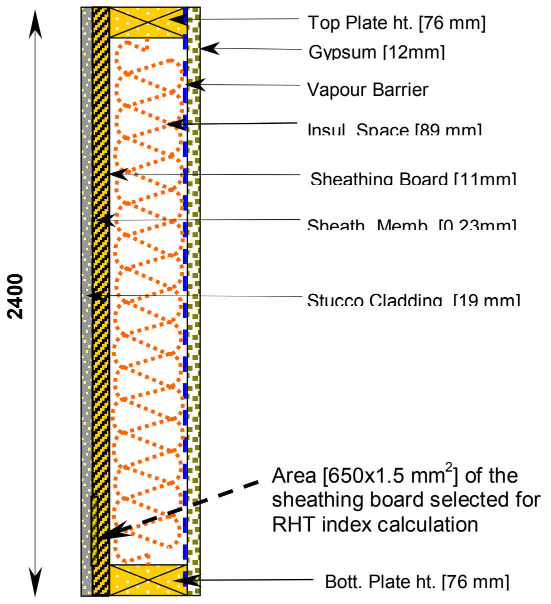

FIGURE 1 Basic wall construction details

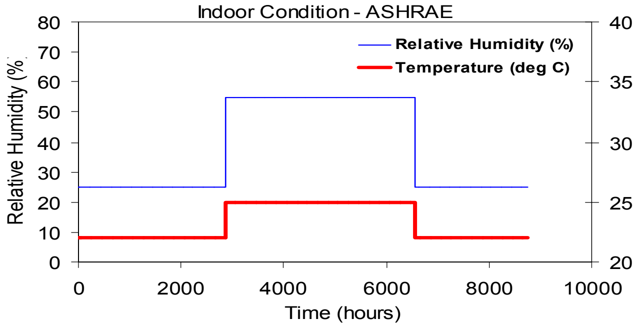

FIGURE 2 Indoor climate – ASHRAE

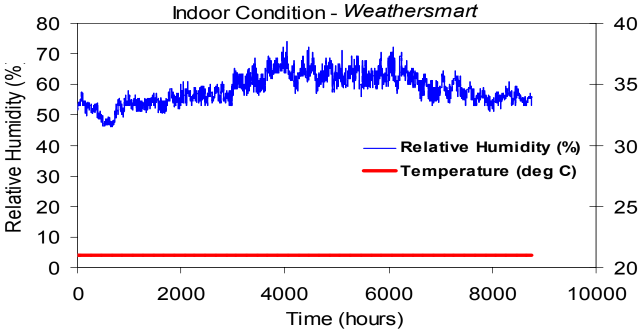

FIGURE 3 Indoor climate – *Weathersmart*

TABLE 1. Parametric variations considered

Simulation ID	Vapour barrier permeance (ng/Pa.s.m^2) + Interior facing	Total vapour permeance of vapour barrier and interior facing (ng/Pa.s.m^2)	Indoor condition
Seven different vapour barriers with ASHRAE specified indoor condition			
VA15-A	15+Coated Gypsum	14.7	ASHRAE (Figure 2)
VA60-A	60+Coated Gypsum	54.8	ASHRAE (Figure 2)
VA100-A	100+Coated Gypsum	86.0	ASHRAE (Figure 2)
VA500-A	500ng+Coated Gypsum	271.9	ASHRAE (Figure 2)
VA1000-A	1000ng+Coated Gypsum	372.5	ASHRAE (Figure 2)
VANC-A	No vapour barrier+Coated Gypsum	591.3	ASHRAE (Figure 2)
VANUC-A	No vapour barrier+Uncoated Gypsum	2753.3	ASHRAE (Figure 2)
Seven different vapour barriers with *Weathersmart* generated indoor condition			
VA15-B	15+Coated Gypsum	14.7	*Weathersmart* (Figure 3)
VA60-B	60+Coated Gypsum	54.8	*Weathersmart* (Figure 3)
VA100-B	100+Coated Gypsum	86.0	*Weathersmart* (Figure 3)
VA500-B	500ng+Coated Gypsum	271.9	*Weathersmart* (Figure 3)
VA1000-B	1000ng+Coated Gypsum	372.5	*Weathersmart* (Figure 3)
VANC-B	No vapour barrier+Coated Gypsum	591.3	*Weathersmart* (Figure 3)
VANUC-B	No vapour barrier+Uncoated Gypsum	2753.3	*Weathersmart* (Figure 3)
Seven different vapour barriers with constant indoor condition			
VA15-C	15+Coated Gypsum	14.7	Constant (21°C, 40% RH)
VA60-C	60+Coated Gypsum	54.8	Constant (21°C, 40% RH)
VA100-C	100+Coated Gypsum	86.0	Constant (21°C, 40% RH)
VA500-C	500ng+Coated Gypsum	271.9	Constant (21°C, 40% RH)
VA1000-C	1000ng+Coated Gypsum	372.5	Constant (21°C, 40% RH)
VANC-C	No vapour barrier+Coated Gypsum	591.3	Constant (21°C, 40% RH)
VANUC-C	No vapour barrier+Uncoated Gypsum	2753.3	Constant (21°C, 40% RH)

5.0 *hygIRC-2D* OUTPUT AND ANALYSIS OF RESULTS

A significant amount of data were generated from *hygIRC-2D* and subsequently post-processed for the detailed evaluation of the simulated hygrothermal response of the various walls through parametric analyses. The results obtained from the typical *hygIRC-2D* output have been further analysed as described in the following paragraphs.

5.1 Typical *hygIRC-2D* Output

The basic outputs from *hygIRC-2D* simulations are the relative humidity (RH) and temperature (T) contour plots (Figure 4) across the wall assembly cross-section (vertical). In this study, these contour plots were generated at midnight, at every 10-day interval for the entire duration of the simulation/exposure period (i.e. 2 years). In order to make quantitative sense of the long-term moisture response of the wall assembly from these outputs, a novel hygrothermal performance indicator called RHT index, derived from the RH and T distribution patterns over a period time as defined in the following paragraphs, has been used.

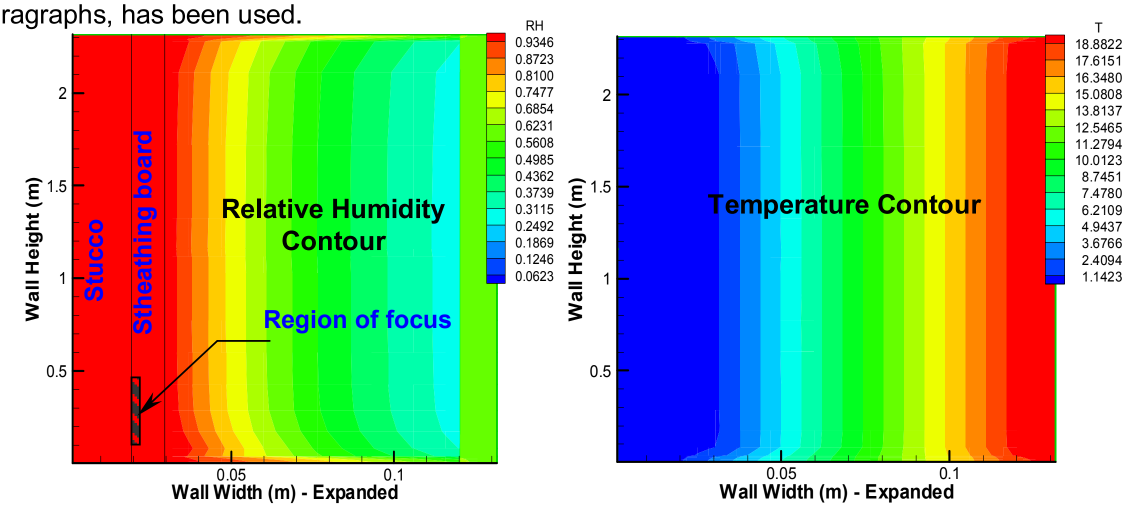

FIGURE 4 Typical outputs from *hygIRC-2D*

5.2 RHT Index

The RHT Index (Kumaran et al. 2003; Mukhopadhyaya et al. 2002; Mukhopadhyaya 2003) can be used to quantify and compare the localized hygrothermal response of any part of the wall component (i.e., 'region of focus', see Figure 4). The 'region of focus' is that part of the wall cross-section where hygrothermal response is the most severe and critical for the long-term moisture performance of the wall assembly. Relative humidity (RH) and temperature (T) at different time steps are the values required to obtain the RHT index. The generic definition of RHT index at the 'region of focus' is:

$$\text{RHT Index} = \sum_{t=1}^{n} \left(\mathrm{RH} - \mathrm{RH}_X\right) \times \left(\mathrm{T} - \mathrm{T}_X\right) \qquad (1)$$

where

RH = relative humidity (%); RHx = threshold RH; T = temperature; Tx = threshold temperature (°C); t = time step or interval when RH and T values are recorded.

During any time step when either or both $\mathrm{RH} \le \mathrm{RH}_X\%$ and $\mathrm{T} \le \mathrm{T}_X$°C, the RHT value for that time step is zero.

The RHT index brings out the long-term localized combined moisture and temperature response of the selected area of the material (i.e. 'region of focus'). The part of the wall component selected in this study for the RHT index calculation, by visual inspection of the relative humidity contour plot (Figure 4), is a thin layer (height 650mm; width 1.5mm) of sheathing board facing the exterior stucco cladding above the bottom plate (Figure 1). User-defined threshold values for RH_X = 95%, T_X = 5°C and a time step or interval of 10 days over the period of two years have been chosen for this study.

6.0 DISCUSSION ON RESULTS

The RHT indices, indicating the long-term moisture response of the wall assembly, calculated for 21 simulations (Table 1) are shown in Table 2 and in Figures 5 to 7. A higher value of RHT index points out a relatively severe moisture response compared to a lower RHT index value. In addition total moisture content of the interior gypsum board for various cases are also plotted in Figures 8 to 10. The significance of these results is to be discussed in the following paragraphs.

Table 2 Parametric variations considered

Simulation ID	RHT Index	Simulation ID	RHT Index	Simulation ID	RHT Index
VA15-A	675	VA15-B	708	VA15-C	675
VA60-A	276	VA60-B	272	VA60-C	268
VA100-A	265	VA100-B	265	VA100-C	257
VA500-A	249	VA500-B	264	VA500-C	240
VA1000-A	247	VA1000-B	266	VA1000-C	238
VANC-A	422	VANC-B	547	VANC-C	338
VANUC-A	377	VANUC-B	497	VANUC-C	290

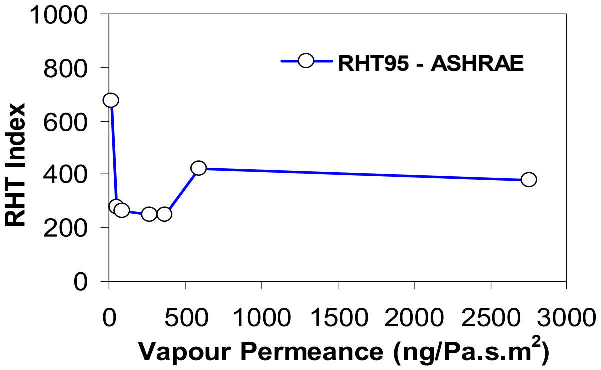

FIGURE 5 RHT Index variation due to different permeance of vapour barrier (ASHRAE indoor condition)

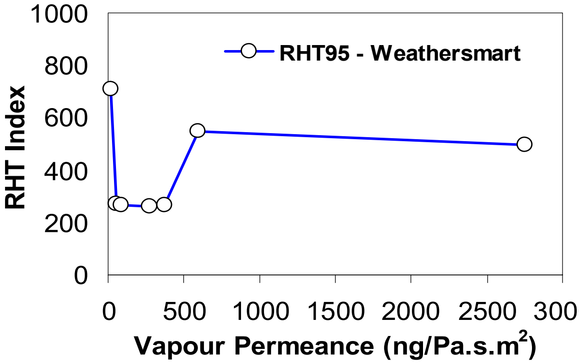

FIGURE 6 RHT Index variation due to different permeance of vapour barrier (*Weathersmart* indoor condition)

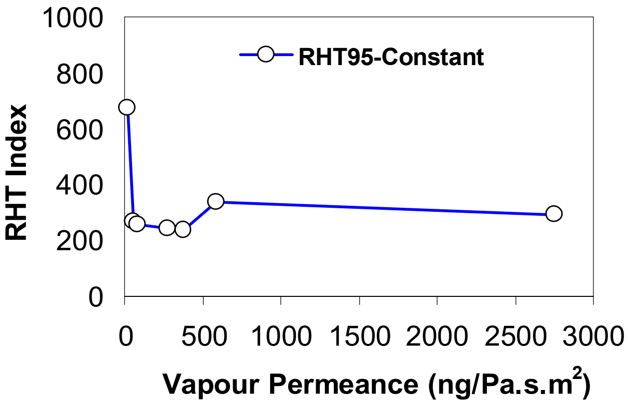

FIGURE 7 RHT Index variation due to different permeance of vapour barrier (Constant Indoor)

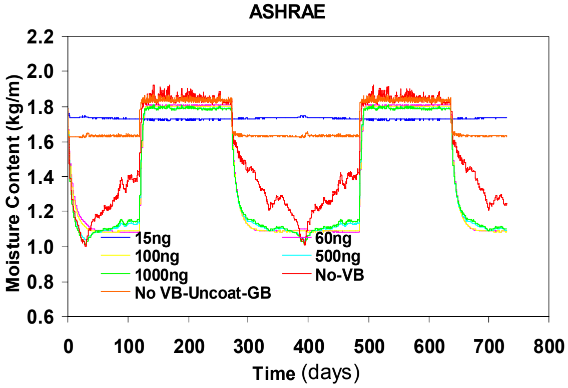

FIGURE 8 Moisture content in interior gypsum facing (ASHRAE Indoor)

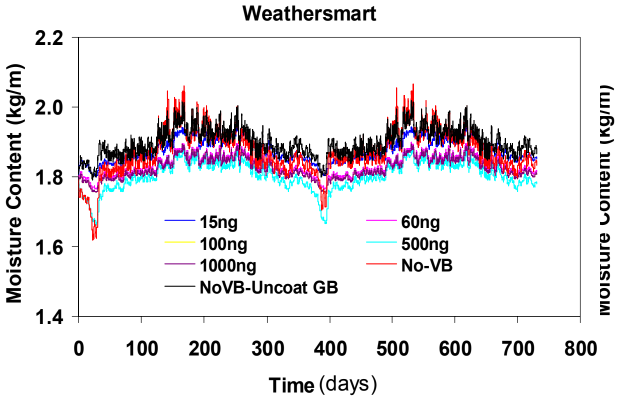

FIGURE 9 Moisture content in interior gypsum facing (*Weathersmart* Indoor)

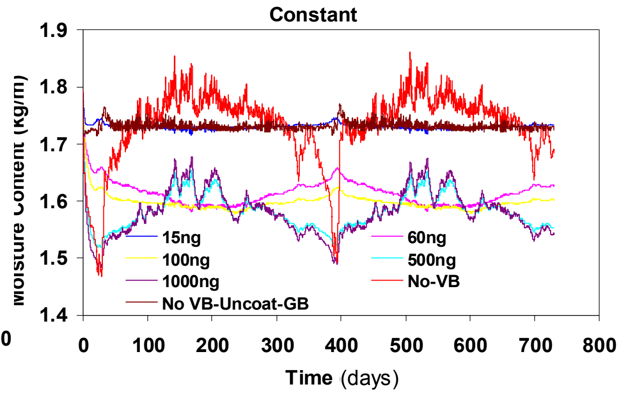

FIGURE 10 Moisture content in interior gypsum facing (*Constant* Indoor)

6.1 Effect of Vapour Permeance of Vapour Barrier

The vapour permeance values of the vapour barriers alone, and the total vapour permeance of the vapour barrier and interior facing for each of the 21 cases are shown in Table 1. The lowest value of the vapour permeance (14.7ng/Pa.s.m^2) is associated with a vapour barrier permeance value of 15ng/Pa.s.m^2 and the highest value of the vapour permeance (2753ng/Pa.s.m^2) is with the case where there is no vapour barrier and the interior facing of the wall is made of uncoated gypsum board.

As shown in Figures 5 to 7, the vapour permeance of the vapour barrier influences the overall moisture response of a wood-frame stucco wall subjected to Vancouver climate. The vapour barrier with the lowest vapour permeance (15ng/Pa.s.m^2), used in this study, produces the most severe moisture response (i.e. the highest value of RHT index). A more vapour permeable vapour barrier can reduce the intensity of the moisture response. However, it is interesting to note that the optimum moisture management (i.e. the lowest RHT index) for the wall assembly cannot be achieved either with the use of the most permeable vapour barrier nor when vapour barrier is entirely removed[+]. The optimum moisture management in this study is obtained when the vapour barrier permeance is between 60 and 1000ng/Pa.s.m^2, and interior gypsum facing board is coated with a primer and latex paint. In fact, the complete removal of the vapour barrier and further reduction of vapour resistance by using uncoated interior gypsum board produces a much higher level of moisture response than the optimum case. Hence, it can be said, as shown in Figures 5 to 7, a vapour barrier with too high or too low vapour resistance would not be a choice that would lead to an optimum moisture management strategy in stucco wall assemblies of the type represented in this study. In Vancouver, as the simulation results show, a vapour barrier that has a vapour permeance value between 60 and 1000ng/Pa.s.m^2 would produce an optimum moisture management. At this stage, the authors are conducting similar studies for other geographic locations in Canada and results from these studies will be reported in due course.

6.2 Effect of Different Interior Climatic Conditions

Results from the simulations (Figures 5 to 7) indicate that the interior conditions (RH and T) considered in this study have very little or no influence on the overall vapour diffusion strategy for optimum moisture management. However, in presence of a vapour barrier with higher vapour permeance or in absence of any vapour barrier, the level of moisture load in the interior climate has a greater influence on the overall moisture response of the wall.

[+] There is a proposed change to the NBC (1995) to remove the requirement for vapour barriers with a minimum 15 ng/(Pa.s.m^2) permeance where there are other low permeance materials in the assembly; only the 60 ng/(Pa.s.m^2) limit would remain.

6.3 Moisture Content in Interior Gypsum Board

It is to be mentioned that the interior facing (gypsum board) also offers some vapour resistance, though not very high, to water vapour moving across the wall assembly. In the presence of a vapour barrier with lower vapour resistance (i.e. providing higher vapour permeance) or in absence of any vapour barrier in the wall assembly, the role and moisture response of the interior facing becomes more critical. In order to investigate this phenomenon the moisture content of the interior gypsum board was varied with time for the entire period of simulation (2 years), the results of which are shown in Figures 8 to 10. These results show that the removal of vapour barrier can significantly increase the moisture content of the interior gypsum board facing.

7.0 SUMMARY OF OBSERVATIONS

The results and discussion presented in this paper on the role of vapour barrier in optimum moisture management can be summarised with several observations as stated below. However, it is to be noted that the observations made in this study are useful, practical and applicable only for the input conditions stated in the paper.

1. Vapour permeance characteristics of the vapour barrier plays an important role in the overall moisture management for the wood-frame stucco wall.
2. Simulation results indicate that an acceptable range of vapour permeance of the vapour barrier to obtain optimum moisture management in the wood-frame stucco wall assembly could be much wider that the prevailing practices. Further studies are required on this issue and in particular the performance of the wall at other geographic locations (other than Vancouver).
3. Removal of the vapour barrier in Vancouver does not produce optimum moisture management in the wood-frame stucco wall.
4. Removal of the vapour barrier from the wall assembly significantly increases the moisture content in the interior gypsum board facing.

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