Development of High Performance Stucco As Cladding Material

Phalguni Mukhopadhyaya[1]
Kumar Kumaran[2], Silvio Plescia[3], John Lackey[4], Nicole Normandin[4] and David van Reenen[4]

ABSTRACT

Recent computer simulation studies at the Institute for Research in Construction (IRC) of the National Research Council (NRC) Canada have indicated that the combined wetting and drying potential of the wood-frame face sealed stucco clad wall is significantly influenced by the water vapour permeability and liquid diffusivity of the stucco material. Lower liquid diffusivity and higher water vapour permeability of the stucco material can positively influence the overall moisture management capacity of the wood-frame face sealed stucco clad wall. This paper presents preliminary experimental results from a pilot research project that aims to use the lessons learned from the simulation studies for the development of new materials or modify existing materials. The results from the experimental study show that it is possible to reduce the water absorption coefficient (a measure of liquid diffusivity) of the stucco material without reducing water vapour permeability through appropriate mix design.

INTRODUCTION

Stucco or portland cement plaster is widely used in the Canadian Housing Industry as an exterior cladding material. On many occasions (e.g. Vancouver, BC; Calgary, Edmonton, AB; Wilmington, NC) wood frame stucco walls have experienced moisture related problems. This phenomenon is particularly accelerated in locations with heavy and sustained rainfall. This has subsequently led to serious long-term performance problems. The financial implications of this problem on the housing industry are enormous by any standard (*Barrett 1998*). Several researchers and technical experts have tried to assess the causes and thereafter determine the ways to solve or limit the moisture management problem in stucco walls. However, solutions to these types of problems are not always easy to find.

Nevertheless recent computer based simulation studies at the National Research Council (NRC) Canada, Institute for Research in Construction (IRC) have demonstrated that the combined wetting and drying potential of the wood frame stucco wall is significantly influenced by the water vapour permeability and liquid diffusivity of the stucco material. A lower liquid diffusivity and higher water vapour permeability of the stucco material can positively influence the overall moisture management capacity of the wood frame stucco wall (*Mukhopadhyaya et al. 2003*). Also, another study at the NRC-IRC showed that among all the major components (stucco, sheathing membrane, sheathing board and vapour barrier) stucco has the most significant variation in the material properties that influence the overall moisture response of the ideal (i.e. without deficiency) stucco walls without rain-screen exposed to Western Canada coastal climate (*Mukhopadhyaya et al. 2002a*). This study also indicated that the combination of maximum[5]

---

[1] Research Officer, National Research Council Canada, Institute for Research in Construction, Ottawa, Ontario, Canada.
[2] Principal Research Officer, National Research Council Canada, Institute for Research in Construction, Ottawa, Ontario, Canada.
[3] Senior Researcher, Technical Research Division, Canada Mortgage and Housing Corporation (CMHC), Ottawa, Ontario, Canada.
[4] Technical Officer, National Research Council Canada, Institute for Research in Construction, Ottawa, Ontario, Canada.
[5] 'Maximum' is based on the water vapour permeability data available for the stucco materials in the NRC-IRC's material properties database.

water vapour permeability and minimum[6] liquid diffusivity would be very desirable characteristics for exterior stucco cladding.

OBJECTIVE

This research project focuses on the possibility of engineering a portland cement stucco material that will limit liquid water entry on its exterior surface and at the same time allow water vapour to dry out of it. This research considers stucco as an isolated material component of the exterior wall system. This project does not investigate system performance of the wall assembly with stucco as a cladding. The effects of imperfections, defects and anomalies typically found in exterior wall systems are beyond the scope of this investigation.

Hence, the primary objective of this project is to engineer a stucco mix design that has the effect of lowering the liquid diffusivity and increasing the water vapour permeability characteristics of the stucco material. The aspects of performance of the engineered stucco material will be compared with the commonly used stucco materials in Canada.

BACKGROUND FUNDAMENTALS

For this project it is very important to understand the basics of water vapour permeability and liquid diffusivity. These two moisture transport properties are described in the following paragraphs.

Water Vapour Permeability

The water vapour permeability of any building material at unit thickness can be defined as the rate of water vapour transmission per unit area per unit of vapour pressure differential under specified test conditions. The vapour diffusion equation is directly used to determine the water vapour permeability of building materials (*Joy and Wilson, 1963*). 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) and vapour pressure (Figure 1). The rate of vapour flow across the specimen, under steady-state conditions (known RH's as constant boundary conditions), is then gravimetrically determined. From these data the water vapour permeability of the material is calculated as:

$$\delta_p = J_v \cdot l/(A \cdot \Delta p) \qquad (1)$$

where,

J_v = Water vapour flow rate across an area A

l = Thickness of the specimen

Δp = Difference in water vapour pressure across the specimen surfaces

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

$$\delta_l = J_v/(A \cdot \Delta p) \qquad (2)$$

ASTM Standard E 96/E 96M - 05, Standard Test Methods for Water Vapour Transmission of Materials, 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 %. For many hygroscopic materials, such as wood and wood products, the water vapour permeability/permeance is a function of the local relative humidity and increases with RH.

---

[6] 'Minimum' is based on the liquid diffusivity data available for the stucco materials in the NRC-IRC's material properties database.

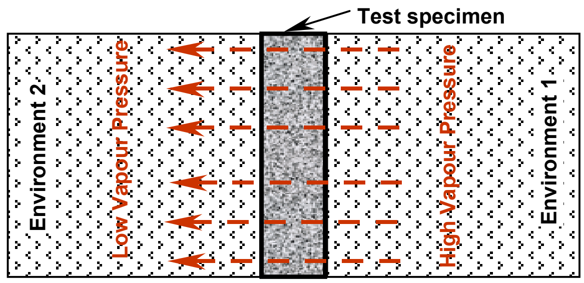

Figure 1 – Schematic of water vapour transmission across a specimen

Liquid Diffusivity

Liquid diffusivity defines the rate of movement of water within a material, induced by a water concentration gradient. A material that allows liquid water diffusion through its boundary surface would change its weight with time when it is brought in contact with liquid water (Figure 2). A schematic plot (*Kumaran 1999*) of the increase in weight of the test specimen versus the square root of the time indicates that the specimen weight increases linearly (Figure 3) before it comes close to the capillary saturation limit. The slope of this linear variation is called the water absorption coefficient (A_w) and can be mathematically written as:

$$A_w = \left(\frac{M_t - M_i}{A\sqrt{t}} \right) \qquad (3)$$

where,
M_t = weight of the specimen after time *'t'*
M_i = initial mass of the specimen
A = liquid contact area of the specimen
t = time.

In this study, water absorption coefficient is taken as a measurement of liquid diffusivity or rate of movement of water within a material (*Mukhopadhyaya et al. 2002b*) in accordance with the ISO Standard ISO 15148:2002 (E).

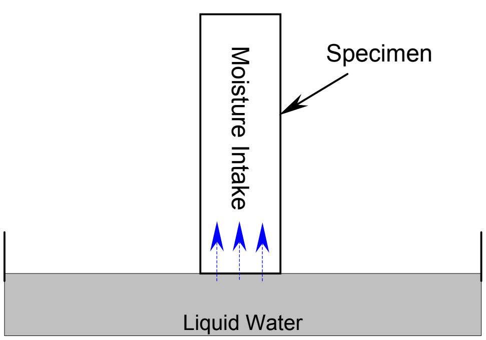

Figure 2 - Moisture movement into a material from surface contact with liquid water

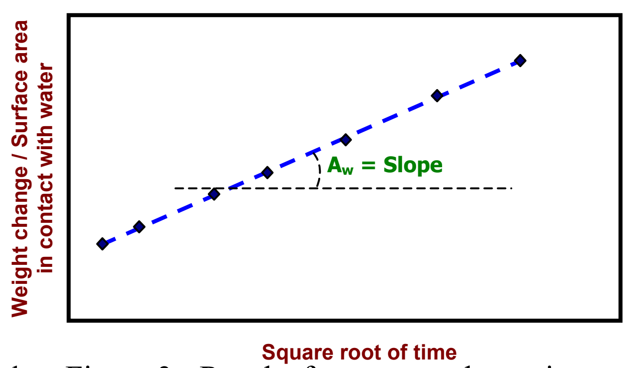

Figure 3 - Results from water absorption test

EXPERIMENTAL WORK

The experimental work was undertaken in two phases: **Phase I** – Preparation and testing of *base case* stucco, and **Phase II** – Preparation and testing of *modified* stucco for high performance.

The objective of the *Phase I* was to establish the basic moisture transport properties, water vapour permeability and water absorption coefficient, of commonly used stucco materials (referred to as *base case* stucco in this report) currently available in Canada. Four stucco mixes were used in this phase, including one that was strictly based on the basic minimum requirement of the National Building Code (NBC) of Canada (1995).

The objective of *Phase II* was to develop a *modified* stucco material that has lower water absorption coefficient but higher water vapour permeability in comparison with the *base case* stucco materials tested in the Phase I.

Preparation of Test Specimens

Three stucco samples were cast for each type of stucco mixes in a custom-built pine wood frame (Figure 4) with internal dimension 380 mm×380 mm.

The total thickness of each stucco sample after curing was approximately 21 mm (Figure 5). The respective thicknesses of scratch and brown coat were approximately 9 mm. The thickness of the finish coat was a minimum of 3 mm.

Metallic mesh conforming to the requirement of the NBC (1995) Canada (Article 9.28.4) was used as stucco lath embedded inside the scratch coat stucco and nailed with the bottom plate of the wood-frame[7] (Figure 4). There was no sheathing membrane placed between the metal lath and the bottom plate of the wood-frame.

The stucco mixes were prepared in conformance with manufacturers' written instructions or in conformance with mix designs outlined in the NBC (1995) Canada (Article 9.28.5.3).

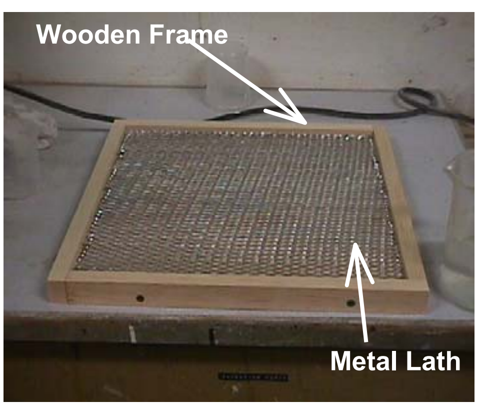

Figure 4 - Custom-built pine wood-frame with metal lath

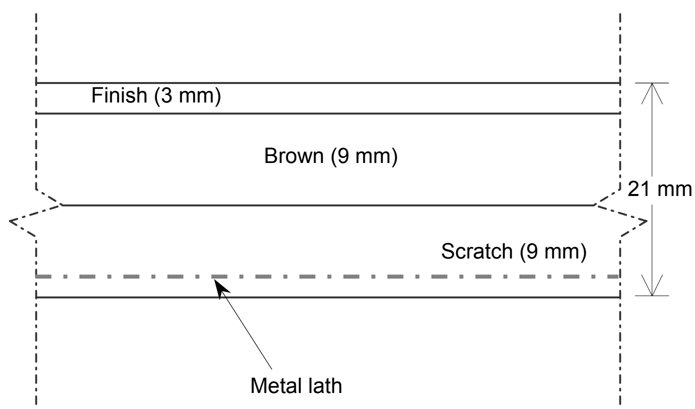

Figure 5 - Schematic three-coat stucco

[7] The stucco materials were tested after curing and removal of the wood-frame.

Phase I - Base Case Stucco

Four stucco mixes, identified as N1, N2, N3 and N4, investigated in Phase I of this study were:

(1) Commercial Stucco I – N1
(2) Commercial Stucco II – N2
(3) Commercial Stucco III – N3
(4) NBC Stucco – N4

N1, N2 and N3 are commercial representative stucco mixes from different regions of the country (Canada). The stucco mixes used were delivered in the laboratory in bags with instructions on the mixing and curing process. These instructions provided the guidelines for the preparation of the specimens. In general, commercial stucco mixes consisted of hydraulic cement, lime, aggregate and additional admixtures to improve workability and physical properties of the stucco mixes. The mix composition of the finish coat, distinctively different from the scratch coat and brown coat, included colour pigment and a water resistive ingredient.

The mix design for the NBC stucco (N4) was in accordance with Part 9 (Article 9.28.5) of the National Building Code (NBC) of Canada (1995). The mix design used for this purpose and the respective NBC (1995) requirements are shown in Table 1. Potable water was added to this mix to achieve required workability. Unlike the commercial stuccos N1, N2 and N3, the NBC stucco N4 had a stone dash finish. The stone chips were partially embedded in the brown coat before the brown coat started to harden.

Table 1 - Mix design for NBC stucco – N4 (by volume)

	Portland Cement	Masonry Cement	Aggregate*
This Study	1	1	7
NBC (1995)	1	1	3.25 to 4 parts per part of cementitious material

**: graded natural sand*

Phase II – Modified Stucco for High Performance

The primary objective of this research project lies with the development of *modified* stucco that will limit liquid water entry on its external surface and at the same time allow water vapour to dry out of it.

Four different options investigated were:

1. Use of hydrophobic coating on exterior surface – M1.
2. Use of hydrophobic aggregate – M2.
3. Use of aggregates coated with hydrophobic chemical– M3.
4. Use of Zinc Stearate as admixture– M4.

Following paragraphs outline the mix-design and construction details for the aforementioned four stucco materials.

Hydrophobic Coating on Exterior Surface – M1

Hydrophobic (i.e. water repelling) materials are those that have low affinity towards liquid water. In fact, when liquid water comes in contact with a surface coated with hydrophobic material, it tends to form discrete droplets on the material surfaces. Low surface tension and lack of active chemical groups on their surface to form "hydrogen-bonds" with water are the reasons behind the water-repelling characteristic of hydrophobic materials.

Hence, it is quite logical to use hydrophobic coating on the exterior face of the stucco to reduce liquid water entry (i.e. low water absorption coefficient). However, it is also to be noted that there remains a possibility that application of hydrophobic coating on the stucco surface may also reduce water vapour transmission capacity (*Carmeliet et al. 2002a,b*).

The chemical name of the hydrophobic coating used on the exterior surface is Triethoxy-N-Octylsilane. This coating was applied directly on the exterior face of the NBC stucco – N4. The exterior surface of the stucco was cleaned and made free from any residue or loose stone dash finish before applying two flood coats of hydrophobic coating with a paintbrush. An estimated application rate was 0.3 litres/m^2 and the coated surface was dried for twenty-four hours before application of the second coat. The stucco samples were cured for at least seven days before conducting water vapour permeability and water absorption tests.

Use of Hydrophobic Aggregate – M2

Hydrophobic aggregates are those that allow free convective air movement through its pores but repel liquid water coming in contact with it. In other words, it is envisaged that the presence of such aggregates in the stucco mix will help to reduce the water absorption capacity of the stucco material without reducing its ability to transport air and water vapour across it.

The hydrophobic aggregates used for this purpose had been obtained from an overseas (Israel) source. The particular type used for this purpose is identified as 'high pH hydrophobic aggregates[8]' (Figure 6). In order to determine the effectiveness and proportion of hydrophobic aggregate, five mix designs (Table 2) were tested and water absorption characteristics were determined. The stucco samples were cast in one coat and had a thickness of approximately 13 mm. Based on the water absorption characteristics of five mix designs (Figure 7), mix design 5 (PC[9]:MC[5]:AG[5]:HA[5] – 1.0:1.0:7.0:1.8) was considered in this study for further investigation because of its lowest measured water absorption coefficient as shown in Figure 7. These specimens had scratch coat, brown coat and stone dash finish (similar to the NBC Stucco – N4).

Table 2 - Various mix designs with hydrophobic aggregate (by volume)

Mix Design	Portland Cement	Masonry Cement	Aggregate	Hydrophobic Aggregate
1 (NBC Stucco – N4)	1.0	1.0	7.0	-
2 (NBC stucco with hydrophobic aggregate)	1.0	1.0	7.0	0.3
3 (NBC stucco with hydrophobic aggregate)	1.0	1.0	7.0	0.6
4 (NBC stucco with hydrophobic aggregate)	1.0	1.0	7.0	1.2
5 (NBC stucco with hydrophobic aggregate)	1.0	1.0	7.0	1.8

[8] A proprietary product.
[9] PC – Portland Cement; MC – Masonry Cement; AG – Aggregate; HA – Hydrophobic Aggregate

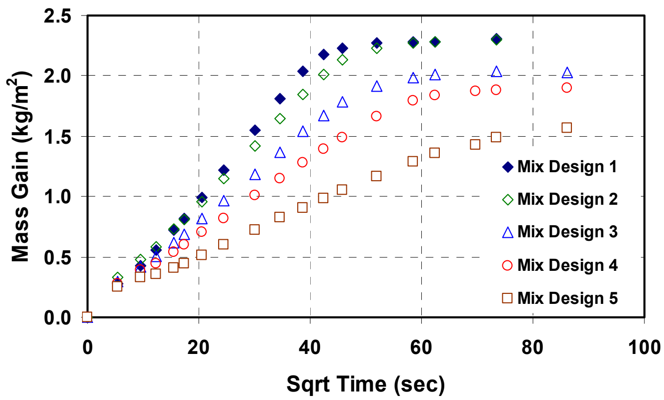

Figure 6 - Hydrophobic aggregate

Figure 7 – Water absorption characteristics of various mixes with hydrophobic aggregate

Use of Aggregates Coated with Hydrophobic Chemical – M3

In this attempt to develop 'high performance stucco' the graded dry natural sand (the same one used for NBC Stucco – N4) was completely soaked in a hydrophobic liquid 'Octyltriethoxysilane' and then dried in ambient condition (22° C, 50% relative humidity) of the laboratory. The hydrophobic liquid 'Octyltriethoxysilane' has the same generic chemical composition as that of the hydrophobic coating (Triethoxy-N-Octylsilane). This treated sand was then used as hydrophobic aggregate for the stucco mix design. The mix design used for this purpose was PC:MC:AG:HA – 1.0:1.0:7.0:1.8 (same as mix design 5).

Zinc Stearate as Hydrophobic Admixture – M4

Zinc Stearate is a zinc soap that repels water. It has been already demonstrated that the use of Zinc Stearate, as an admixture with lime-pozzolana plaster, can lead to a significant decrease of liquid water transport properties and water vapour sorption capacity of that plaster (*Černý et al, 2004*). However, presence of Zinc Stearate, as an admixture, can significantly decrease or slightly increase the water vapour permeability of the lime-pozzolana plaster, depending on the nature of the pozzolanic admixture used in the lime plaster (*Černý et al, 2004*).
In this study, Zinc Stearate (fine, soft white powder, insoluble in water) was used as an admixture to the NBC Stucco – N4 mix design. The mix design ratios are shown in Table 3.

Table 3 - Stucco mix design with Zinc Stearate admixture (by volume)

Portland Cement	Masonry Cement	Aggregate	Zinc Stearate
1	1	7	0.25

RESULTS

A total of eight types of stucco mixes were considered in this study. Four of them, *base case* stucco in Phase I, were tested to establish the water vapour permeability and water absorption characteristics of stucco materials commonly used in Canada. The remaining four stucco mixes, in Phase II, were the stucco materials that were *modified* with the intent of developing a *high performance* stucco material that would have lower water absorption coefficient and higher water vapour permeability in comparison with the *base case* stucco materials tested in Phase I. The experimental results obtained from the Phase I and Phase II of the study are presented in the following sections.

Base Case Stucco

The water vapour permeability and water absorption coefficients of the four *base case* stucco materials are shown in Table 4.

Water vapour permeability of the *base case* stucco materials at 75 percent mean RH (i.e. wet cup method) were found to be always higher than the values measured at 25 percent RH (i.e. dry cup method). NBC Stucco – N4 was the most water vapour permeable and Commercial Stucco III – N3 was the least water vapour permeable stucco among the four *base case* stucco materials considered in this study. These values of water vapour permeability compare very well with the values obtained from the contemporary literature (*Kumaran et al. 2000; Kumaran 2002; Kumaran et al. 2002*) for the stucco materials (Table 5). The water absorption coefficient values of four *base case* stucco materials show that NBC Stucco – N4 was the most and Commercial Stucco II – N2 was the least liquid water absorbent material. The water absorption coefficient values obtained from recent literature (*Kumaran et al. 2000; Kumaran 2002; Kumaran et al. 2002*) are shown in Table 6.

The values of measured moisture transport properties (i.e. water vapour permeability and water absorption coefficient) clearly indicate that the *base case* stucco materials/mixes chosen for this study are very much representative of the contemporary stucco materials used in Canada.

It is also to be noted from Table 4 that the *base case* stucco with very low water absorption coefficient does not have very high water vapour permeability. Thus based on the results presented in Table 4, a high performance stucco consists of the best attributes of the four *base case* stuccos that would have dry cup water vapour permeability 4.7×10^{-12} $kg.m^{-1}.s^{-1}.Pa^{-1}$ or higher, wet cup water vapour permeability 10.1×10^{-12} $kg.m^{-1}.s^{-1}.Pa^{-1}$ or higher, and water absorption coefficient 0.0008 $kg.m^{-2}.s^{-½}$ or lower.

Table 4 - Water vapour permeability of *base case* stuccos

Specimen ID	Water Vapour Permeability ($kg.m^{-1}.s^{-1}.Pa^{-1}$)		Water Absorption Coefficient ($kg. m^{-2} .s^{-½}$)
	Dry Cup (25% mean RH)	Wet Cup (75% mean RH)	
N1	2.807×10^{-12}	5.325×10^{-12}	0.0095
N2	1.223×10^{-12}	3.818×10^{-12}	0.0008
N3	0.282×10^{-12}	1.826×10^{-12}	0.0039
N4	4.738×10^{-12}	10.14×10^{-12}	0.0235

Table 5 - Water vapour permeability of various stucco materials from literature

Specimen ID	Mean		Lower Limit		Upper Limit	
	Water Vapour Permeability (kg.m^{-1}.s^{-1}.Pa^{-1}) × 10^{-12}					
	Dry Cup	Wet Cup	Dry Cup	Wet Cup	Dry Cup	Wet Cup
VAN I to VAN III* (8 Stucco Specimens)	2.45	6.05	1.59	3.93	3.31	8.17
ASHRAE**	1.06	2.53	-	-	-	-
MEWS – I***	1.68	5.03	-	-	-	-
MEWS - II***	1.04	2.57	-	-	-	-
MEWS - III***	2.64	3.62	-	-	-	-

** Kumaran et al. 2000; ** Kumaran 2002; *** Kumaran et al. 2002*

Table 6 - Water absorption coefficient of various stucco materials from literature

Specimen ID	Water absorption Coefficient (kg. m^{-2} .s$^{-½}$)	Specimen ID	Water absorption Coefficient (kg. m^{-2} .s$^{-½}$)
VAN I*	0.0072	VAN VII*	0.0110
VAN II*	0.0110	VAN VIII*	0.0160
VAN III*	0.00058	ASHRAE**	0.0120
VAN IV*	0.0300	MEWS - I***	0.0050
VAN V*	0.0330	MEWS - II***	0.0123
VAN VI*	0.0390	MEWS - III***	0.0074

** Kumaran et al. 2000; ** Kumaran 2002; *** Kumaran et al. 2002*

Modified Stucco for High Performance

As mentioned above, a desirable "high performance stucco" is the one that has higher than or equal the *base case* stuccos water vapour permeability and lower than or equal *base case* stuccos water absorption coefficient. Four *modified* stucco mixes were tested for this purpose and the results are shown in Figures 8 and 9.

These experimental results show that the stucco mix M2, with hydrophobic aggregate, has the highest water absorption coefficient and the stucco mix M4, with Zinc Stearate admixture, has the lowest water absorption coefficient. However, the stucco mix M1 (hydrophobic coating on exterior surface) and M3 (aggregates coated with hydrophobic chemical) have relatively low water absorption coefficients close to the value of stucco mix M4. Moreover, the water absorption coefficients of all these three stucco mixes (M1, M3 and M4) are closer to the lowest value of water absorption coefficient observed in the case of *base case* stucco (Figure 8).

The measured water vapour permeability values of the four *modified stucco* materials show that the stucco mix M1 has the lowest dry and wet cup water vapour permeability. The results indicate that the hydrophobic coating, used in this study, on the exterior surface of the stucco (i.e. stucco mix M1) can reduce the water absorption phenomenon, however, this benefit comes with accompanying reduction in the water vapour permeability.

Stucco mix M4 shows the highest dry cup water vapour permeability and it is higher than the highest observed in the *base case* stucco mixes (N4 in Figure 9). However, the wet cup water vapour permeability of this stucco is almost the same as the dry cup value (i.e. water vapour permeability does not increase with the increase of relative humidity). In fact, the dry cup water vapour permeability of stucco mix M2, M3 and M4 are all higher than the highest value observed in the case of *base case* stucco. On the other hand stucco mix M3 (aggregates coated with hydrophobic chemical) has the highest wet cup water vapour permeability value and this value is very close to the maximum wet cup value observed in the *base case* stucco mixes (N4 in Figure 9).

DISCUSSION

Figures 8 and 9 clearly indicate that in the *base case* stucco mixes (N1, N2, N3 and N4), the highest water vapour permeability and the water absorption coefficient values lie with the same stucco mix. However, that is not the case with the trial *modified* stucco mixes. In particular, stucco mixes M3 (aggregates coated with hydrophobic chemical) and M4 (zinc stearate as admixture) show very promising results with relatively low water absorption coefficient combined with high water vapour permeability. However, these are all trial mixes and there exists scope for further refinement and optimisation of these stucco mix designs. It is well known that water vapour permeability and water absorption coefficient/liquid diffusivity are the two most important moisture transport properties that govern the overall moisture response and management capability of the wall systems with stucco claddings (*Mukhopadhyaya et al. 2003, Künzel et al. 2004*). However, it is also to be noted here that there are other hygrothermal properties (e.g. sorption isotherm, air permeability etc.) also that also may have some secondary influence on the overall moisture response of the wood-frame stucco wall systems. Apart from these, the effect of the desirable hygrothermal properties of the *modified* stucco on the moisture response of wall systems with stucco claddings also needs to be investigated. Further investigation on all aforementioned issues will be carried out in a separate project at the NRC-IRC in the coming days and will be reported in due course[10].

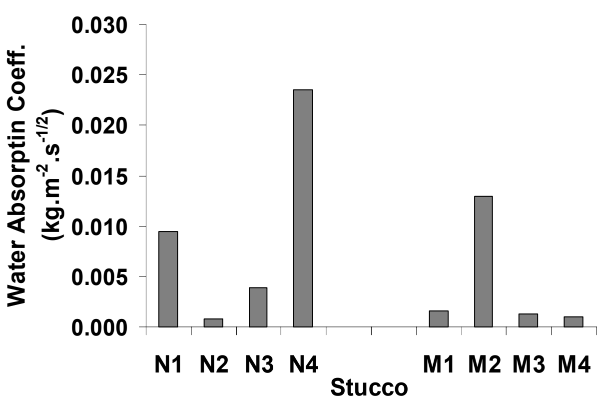

Figure 8 - Water vapour absorption coefficient of *base case* (N1, N2, N3 & N4) and *modified* stucco materials (M1, M2, M3 & M4)

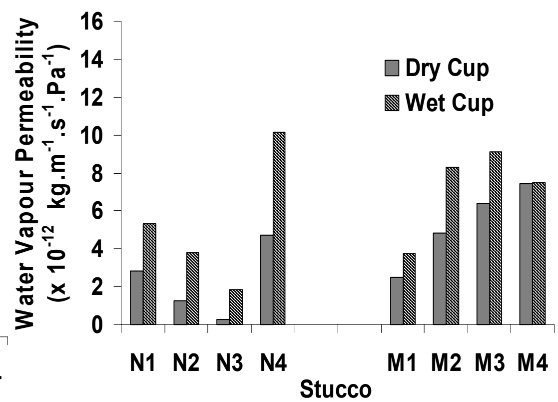

Figure 9 - Water vapour permeability of *base case* (N1, N2, N3 & N4) and *modified* stucco materials (M1, M2, M3 & M4)

[10] After submitting this paper, hygrothermal simulations have been carried out to compare the performance of wood-frame stucco walls with *base case* and *modified* stucco cladding. The results indicate a significant improvement in the moisture management capability of the wood-frame stucco walls with *modified* stucco (*Mukhopadhyaya et al. 2007*) while compared with *base case* stucco walls.

CONCLUSIONS

1. The results from this experimental study show that it is possible to reduce the water absorption coefficient of the stucco material significantly without reducing water vapour permeability through appropriate mix design.
2. Hydrophobic coating used in this study on the exterior face of the stucco appears to reduce the water absorption coefficient and water vapour permeability simultaneously. The effects of other hydrophobic coatings may or may not be the same.
3. Use of aggregates coated with hydrophobic chemical and use of zinc stearate as admixture in the stucco mix seem to be two very promising options to develop high performance stucco materials that have relatively lower liquid water absorption capacity but higher water vapour transmission capacity compared to the commonly stucco materials used in Canada.
4. It is to be mentioned that this is only a pilot study that investigated the possibility to develop high performance stucco material that has lower water absorption capacity and higher water vapour permeability at the same time. This preliminary study on small-scale specimens shows positive results. However, further experiments and analyses on the overall hygrothermal behaviour of the material and wall systems are required to progress further from the findings of this pilot study.
5. Further research into the durability of the stucco properties is required before conclusions can be made with respect to the long-term in service performance of the stucco mixes developed in this study.

ACKNOWLEDGEMENT

The Canada Mortgage and Housing Corporation (CMHC) and the National Research Council Canada (NRCC) funded this research pilot project jointly. Authors would also like to thank SilCoat Ltd. (Israel) for supplying hydrophobic sand and many anonymous material suppliers who provided raw materials for this research project.

REFERENCES

ASTM : E 96/E96 M (2005). Standard test methods for water vapour transmission of materials. *Annual Book of ASTM Standards*. American Society for Testing and Materials, West Conshohocken, PA, USA.

ISO 15148:2002 (E) "Hygrothermal performance of building materials and products - Determination of water absorption coefficient by partial immersion," *International Organization for Standardization*, www.iso.org.

Barrett, D. (1998) "The renewal of trust in residential construction - Commission of inquiry into the quality of condominium construction in British Columbia" Submitted to the Lieutenant-Governor in Council *Government of British Columbia* http://www.hpo.bc.ca/Overview/Barrett1/.

Carmeliet, J., Houvenaghel, G., Van Schijndel, J., and Roels, S. (2002a) "Moisture Phenomena in Hydrophobic Porous Building Material. Part 1: Measurements and Physical Interpretations", *International Journal for Restoration of Buildings and Monuments*, Vol. 8, No. 2/3, pp. 165-183.

Carmeliet, J., van Besien, T., and Roels, S. (2002b) "Moisture Phenomena in Hydrophobic Porous Building Material. Part 2: Measurements and Modelling", *International Journal for Restoration of Buildings and Monuments*, Vol. 8, No. 2/3, pp. 185-203.

Černý, R., Kunca1, A., Tydlitát, V., Tesárek, P., Drchalová, J., and Rovnaníková, P., (2004) "Hygric, thermal and mechanical properties of lime plasters with pozzolanic admixtures", *Proceedings of CIB W40 Task Group Meeting on Heat and Moisture Transfer in Buildings*, Glasgow, UK.

Joy F. A. and Wilson, A. G., (1963) "Standardization of the dish method for measuring water vapour transmission," *Proceedings of the International Symposium on Humidity and Moisture*, Washington, D. C., Vol. 4, Chapter 31, pp 259-270.

Kumaran, M. K. (1999) "Moisture diffusivity of building materials from water absorption measurements," *Journal of Thermal Envelope and Building Science*, Technomic Publishing Co., Vol. 22, April, pp. 349-355.

Kumaran, M.K. (2002), "A thermal and moisture transport property database for common Building and insulating materials", *Final Report from ASHRAE Research Project 1018-RP*, pp. 1–229.

Kumaran, K., Lackey, J., Normandin, N., van Reenen, D. and Tariku, F. (2002). "Summary report from Task 3 of MEWS project". *Institute for Research in Construction*, National Research Council, Ottawa, Canada, (NRCC-45369), pp. 1-68.

Kumaran, M.K., Lackey, J., and Normandin, N. (2000), "Hygrothermal Properties of Eight Stucco samples from the field: information from a joint research project with CMHC". Client Report B1013, *Institute for Research in Construction*, National Research Council Canada, pp. 10.

Künzel, H. M., Künzel, H. and Holm, A. (2004) "Rain Protection of Stucco Facades", Performance of Exterior Envelopes of Whole Buildings IX International Conference, Clearwater, Florida, USA, pp. 1-7.

Mukhopadhyaya, P., Goudreau, P., Kumaran, M. K. and van Reenen, D. (2002a). "Influence of material properties on the hygrothermal response of an ideal stucco wall - Results from hygrothermal simulations". *6th Nordic Building Physics Symposium 2002*, Trondheim, Norway, pp. 611-618.

Mukhopadhyaya, P., Goudreau, P., Kumaran, M. K. and Normandin, N. (2002b) "Effect of surface temperature on water absorption coefficient of building materials," *Journal of Thermal Envelope and Building Science*, 26, (2), pp. 179-195.

Mukhopadhyaya, P., Kumaran, M.K., Tariku, F., and van Reenen, D. (2003). "Final report from Task 7 of MEWS project at the Institute for Research in Construction : Long-term performance: predict the moisture management performance of wall systems as a function of climate, material properties, etc. through mathematical modeling", Research Report, *Institute for Research in Construction*, National Research Council Canada, 132, pp. 384, February 01, 2003, (IRC-RR-132), URL: http://irc.nrc-cnrc.gc.ca/fulltext/rr132/.

Mukhopadhyaya, P., Kumaran, K., Plescia, S, Lackey, J., Normandin, N. and van Reenen, D., (2007) "Development of High Performance Stucco for Optimum Moisture Management in Wood-frame Stucco Walls', Submitted for review.

National Building Code (NBC) of Canada. 1995. Part 9, *National Research Council Canada*, Ottawa.