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Hygrothermal system-performance of a whole building

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Abstract

In this paper the full house hygrothermal performance of an aerated concrete wall system is examined for the hot and humid climate of Miami. The results clearly demonstrated the limited drying potential for the wall system in that climate. The selected exterior thermal insulation strategies and interior vapor control strategies in this study show the critical behavior of the full house with respect to drying initial construction moisture. Moisture related problems such as mold growth are simulated and discussed. From these results moisture control strategies are identified for the whole house hygrothermal performance. © 2001 Published by Elsevier Science Ltd.

Keywords: Moisture control; Moisture engineering; Building envelope modeling; Whole building performance; Aerated concrete

1. Introduction

Today building design criteria are: (a) energy efficiency, (b) minimization of environmental impact and (c) protection of the health and safety of the inhabitants. While critical information can be obtained by investigating the one to one relationships of a building envelope to interior and exterior environments, the total behavior of the actual whole building is not accounted for. Simultaneous heat and mass transfer between building envelopes and indoor air is complicated and expensive to measure in laboratory or field experiments. Numerical modeling becomes an attractive alternative as it is important in understanding and extrapolating experimental results, as well extending and optimizing building performance.

In this paper, the individual hygrothermal performances of each wall, roof, floor sections and the mechanical system which include the direct and indirect coupling of the individual parts of the system are investigated.

The numerical model used in this paper solves simultaneous heat and mass transfer between building envelopes and indoor air and it was validated using the field measurements [1–3]. The validation results showed that the model is able to predict the transfer of water vapor, CO_2 and SF_6 between the building envelope and air. The numerical model was then applied to investigate water vapor transfer and sorption for different weather conditions and for buildings with light weight wood frame and heavy aerated concrete walls. These results showed that water vapor transfer is very important during warm weather and can reduce the indoor relative humidity by up to 30% RH, which can significantly improve comfort in rooms with intermittent moisture sources. During cold weather, water vapor transfer can increase the minimum indoor humidity, which also improves comfort. In buildings with effective and correctly dimensioned cooling and humidity controls the effects of mass transfer can be seen more clearly in the performance of the HVAC-systems than in the indoor air conditions.

Moisture transport through a building envelope influences not only the durability, indoor air quality, health and safety of the inhabitants, but also the energy efficiency of the envelope system. The influences of moisture transport are experienced differently in light weight (hygroscopic) or heavy weight (moisture massive) building envelope systems. Many recent, moisture-related failures of wood frame construction in low-rise residential and steel frame in high-rise residential/commercial buildings have put a significant pressure to change construction codes in North America. Indeed a recent failure of a moisture massive envelope system (School Building) [4] composed of aerated concrete blocks in Florida, clearly demonstrates the need for proper moisture control analysis of building systems. However, solutions to moisture-induced problems may be difficult to achieve when several interacting mechanisms of moisture transport are present. Moisture can exist in three phases, vapor, liquid and solid phase (ice).

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Nomenclature

A	area, m^2
c_p	specific heat capacity, J/kg K
q	flux, kg/m^2,s or W/m^2
S	source term, kg/m^3 s or W/m^3
t	time, s
T	temperature, °C
u	moisture content in porous material, kg_{water}/kg_{dry} material
V	volume, m^3
x	absolute humidity (in air), $kg_{water}/kg_{dry\ air}$
ρ	density, kg/m^3

Superscripts

n	timestep, old time
$n+1$	timestep, new time
iter	iteration step

Subscripts

a	air

During transition, moisture can change phases by evaporation, condensation, sublimation, freezing and thawing mechanisms. Research is continuously upgrading existing understanding on these complicated issues. With the help of simulation models the interactions between the building envelope and indoor climate can be understood better enabling the designs of passive methods to help control indoor air conditions [1–3,5].

In many hot and humid climates, conventional air conditioning units are unable to meet the latent load and the relative humidity exceeds the comfort threshold of 60% RH. This has led to the growing application of heat and moisture transfer devices which can reduce the latent load on air conditioning units [6–10]. With these devices it is possible to provide an acceptable indoor climate even in hot and humid climates. Nevertheless, there is a desire to develop more passive and less energy intensive methods of moderating the indoor environment. These passive methods are gaining popularity because they are energy conscience and environmentally friendly. In hot and humid climates, passive methods could help to reduce the peak cooling demand thereby reducing the required capacity of cooling units and electrical demand charges. In more moderate climates, where air conditioning is seldom used, these passive methods may make it possible to provide acceptable indoor climate without the need of air conditioning.

Recently, a new approach to building envelope durability assessment has been introduced, and is becoming an acceptable norm in North America. The approach employs experimental and advanced modeling analysis to predict the long-term performances of building envelope systems to various levels of interior and exterior environmental loading. This permits the comparison and ranking of wall systems with respect to an overall hygrothermal performance. Elaborate experiments are conducted to measure the various hygrothermal properties such as sorption and suction isotherms, vapor permeabilities, liquid diffusivities, and drainage which are then complimented with full scale laboratory building envelope testing to determine system and sub-system performances. Modeling is then initiated to predict the hygrothermal performances of the individual building envelope part. This approach has been termed as Moisture Engineering [11,12].

Further advances in the area of moisture engineering have currently been achieved by taking a broader wholistic approach to moisture design. In most applications, building envelope designers attempt to predict the hygrothermal performance of an individual building envelope, for example a wall, roof or basement by uncoupling the system not only to the interior environment but the interactions of the other envelope components to both the exterior and interior environments. This one-to-one interaction of a small part (section of a wall system perhaps) of a building is termed today as state-of-the-art. The stand-alone analysis of specific envelope parts is important in understanding the influences of various controlling elements (vapor retarder, air barriers, building papers) in terms of their effect on the hygrothermal performance of the envelope, but provide limited performance information on the overall heat and mass transfer of a building. An iterative open loop approach of complete hygrothermal analysis of a building is demonstrated which requires the direct coupling of all building envelope systems with the interior environment and mechanical systems (HVAC) and the exterior environmental loads.

In this paper, the authors present a new model and approach to wholistic moisture engineering analysis. This paper demonstrates this approach by employing advanced moisture engineering modeling. An application of this wholistic moisture engineering approach is performed to quantify the drying performance of an aerated concrete block building. All building elements, such as the walls and roofs are included in the analysis. The source of water considered is due to the initial construction moisture in the aerated concrete block. The study will attempt to shed some light in some of the issues present in the integrated moisture performance of a complete building.

2. Objectives of present study

The present work is concerned with the hygrothermal performance (drying potential) of a particular aerated concrete block home subjected to two selected vapor diffusion control strategies. The objective of the work was to determine the long-term hygrothermal performance of the building to various vapor control and thermal insulation strategies while subjecting the exterior boundary to real weather data (including temperature, vapor pressure, wind speed and orientation, solar radiation, sky radiation, cloud indexes and rain). A wholistic approach is employed by using moisture engineering principles that integrate, intensive numerical analysis and accurately defined material property measurements. The weather data used in this study analysis are representative of a hot and humid climate found in the south east coast of United States (FL).

3. Vapor control theory

Moisture entry into the wall structure can be caused mainly by five processes: initial construction moisture, vapor diffusion, liquid diffusion, water leakage and moist air leaking inward or outward (being more important for cold climates) through the building envelope. The present study is concerned with moisture transport due to vapor and liquid diffusion throughout the wall. Additional factors of significant importance are the overall integrity of the building material (i.e. cracks and openings), the interface contact and surface moisture resistances, but have not been included in this analysis. The application, location and selection of the vapor retarders is strongly dependent on wall design (whether or not special buffer zones have been provided) and on climatic conditions.

4. Material-property determination

Hygrothermal material properties for aerated concrete and interior and exterior stucco were extracted from a paper presented by one of the authors [13].

4.1. Water vapor permeance and liquid diffusivity

The water vapor transmission characteristics of aerated concrete, and interior and exterior stucco layers were determined according to the modified ASTM E96 Test Method for water vapor transmission of materials. The properties for the liquid diffusivity were also measured using a gamma-ray spectrometric method, and these were included in the numerical analysis.

5. Description of the model

A new model, developed by the authors provided a structured framework allowing the integration the individual heat, air and moisture performances of various oriented walls systems and roof assemblies, by lumping the building dependent geometries to the interior and exterior environment as well as the mechanical equipment of the building. The open modular structure of this building envelope moisture engineering model allows outputs of any hygrothermal model to be assembled and incorporates a feedback loop control, such that thermal and moisture fluxes are directly included in the indoor air conditioning model. Inclusion of the effects of wind-driven rain, and water point sources can be incorporated, which makes this approach unique. The solution method uses the so-called delta-form Eq. (1) in which the linearized equations can be maintained on the left-hand side of the equations and on the right-hand side the ‘exact’ equations can be used with known values from the previous time step or from previous iterations. The coupling of the indoor air and the other components of the system is enabled by iterating and using relaxation factors. The components that cannot be directly coupled with the indoor air balance see only the known value from the previous time or iteration step. Relaxation factor changes as a function of convergence. Delta-form equation is used in the format:

$$\begin{aligned}
&A\frac{\Delta u^{n+1}}{\Delta t} = f(u_i, v_j, \ldots)^{n+1},\\
&\Delta u^{n+1} = u^{n+1} - u^n; \quad \Delta t^{n+1} = t^{n+1} - t^n,\\
&\Downarrow\\
&A\frac{(u^{n+1} - u^{\text{iter}} + u^{\text{iter}} - u^n)}{\Delta t}\\
&\quad = f(u_i, u_j, \ldots)^{\text{iter}} + \sum \frac{\partial f}{\partial u_k^{\text{iter}}},
\end{aligned} \tag{1}$$

$$V\rho_a c_p \frac{\partial T_a}{\partial t} = \sum_{k=1}^{n} q_k A_k + \sum_{k=1}^{n} S_i, \tag{2}$$

$$V\rho_a \frac{\partial x_a}{\partial t} = \sum_{k=1}^{n} q_{m,k} A_k + \sum_{k=1}^{n} S_{m,i}, \tag{3}$$

$k = \text{walls, roofs, mechanical system}, \ldots,$

where V is the volume of the indoor air, q_k is the heat flux through the surface A_k calculated by the model that calculates the heat and mass balance in the structures and in mechanical components. S is a source term that may or may not have a feedback loop back to the indoor air temperature or humidity. T_a and x_a are the temperature and moisture ratio ($\text{kg}_{\text{water}}/\text{kg}_{\text{dry air}}$) of the indoor air.

6. Problem description

The hygrothermal performance (drying potential) of an aerated concrete block home as depicted in Fig. 1 was analyzed with two different interior vapor control strategies. The house was rectangular in cross section (15×20 m) and the roof was inclined at 20°. Windows and doors occupied approximately 20% of the exterior building surface, and were represented with U-value thermal performances

Fig. 1. Schematic of analyzed home.

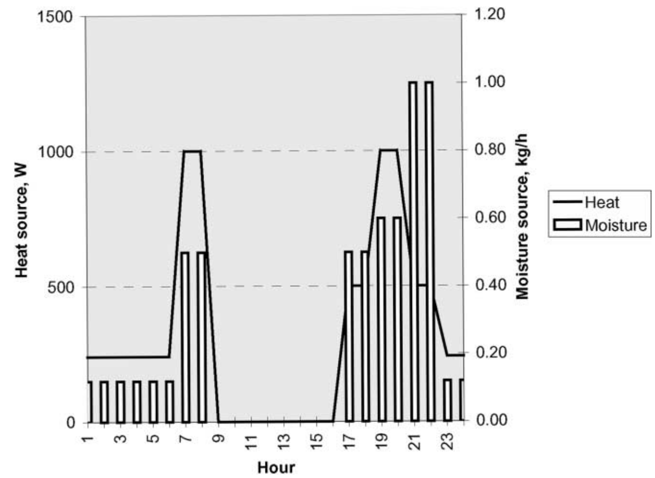

Fig. 2. Heat and moisture sources in the building at various times of day. Daily heat and moisture sources total 7.9 kWh and 6.1 kg.

of 2.0 W/m^2 K. The roof consisted of 300 mm mineral wool insulation with polyethylene vapor/air retarder and gypsum board on the interior side.

Two additional cases were simulated; one with 25 mm expanded polystyrene installed on the exterior of the building and the other without the insulation. This was conducted to determine the influence of exterior insulation (thermal performance) on the drying performance of the building.

The walls were composed of the following layers starting from the exterior to interior: a 12.5 mm exterior grade acrylic stucco, a 198.4 mm aerated concrete block and a 6.35 mm interior gypsum plaster. The inside surface of the gypsum plaster was coated with a vapor open paint (permeance approximately 200 ng/m^2 s Pa or 4 perms). Variations of this wall consisted of the cases with vapor retarder paint in the interior side of the wall and without this vapor control. The aerated concrete was initially assumed at 22% moisture content. This represents a very wet initial moisture condition in the aerated concrete layer. All other layers in the wall system were assumed to be in equilibrium at 80% relative humidity.

Wind-driven rain water was included in the analysis, the exterior surface were exposed to the amount of rain that typically hits a vertical wall. This amount depends on the intensity of precipitation, wind speed and wind direction as well as the location on the wall surface [14].

The wall was exposed to outside air temperature, relative humidity, wind speed and orientation and rain precipitation that varied hourly according to the weather data from the selected location (Miami). The simulations were carried out for a three year exposure starting on 1 August. The solar radiation and long wave radiation from the outer surfaces of the wall were included in the analysis. In this study, no air infiltrating or exfiltrating was considered; therefore the primary mode of water transmission is due to diffusion processes, both vapor and liquid transport. For the simulations of the wall and roof assemblies the LATENITE 3.0 VTT version was employed for all simulations. Simulations were performed at VTT.

7. Boundary conditions

Internal conditions were analytically resolved by the transport of moisture and heat through the wall systems and the mechanical heating and air conditioning controls.

The interior inhabitants were also modeled as heat and moisture sources and sinks, by allowing daily variations of thermal and moisture production and dissipation (allowing the inhabitant to open a window when a certain set-point interior temperature was reached (24°C)). A typical 24 h schedule is depicted in Fig. 2 for a 2 adult and 2 children household with moderate moisture sources. The interior space was dehumidified, and a 0.3 air change per hour was assumed for air quality purposes. The Solar and Meteorological Surface Observation Network 1961–1990 [15] data for Miami during the years 1961–1963 were used in the simulations. The 1961 yearly average temperature and vapor pressure in Miami is 24.2°C, and 2225 Pa, respectively.

A rectangular building (15 $\times$ 20 m) was modeled, the heat and mass transfer coefficients for external and internal surfaces were variable depending on the temperature, the wind speed and orientation (only for the exterior surfaces). The Lewis relationship between heat and mass transfer was assumed. The heat and mass transfer coefficients for the exterior were assigned values that varied from hour to hour depending on the exterior weather conditions.

8. Simulation results

Figs. 3 and 4 show the heating, cooling and dehumidifying behavior of the building for various conditions. The

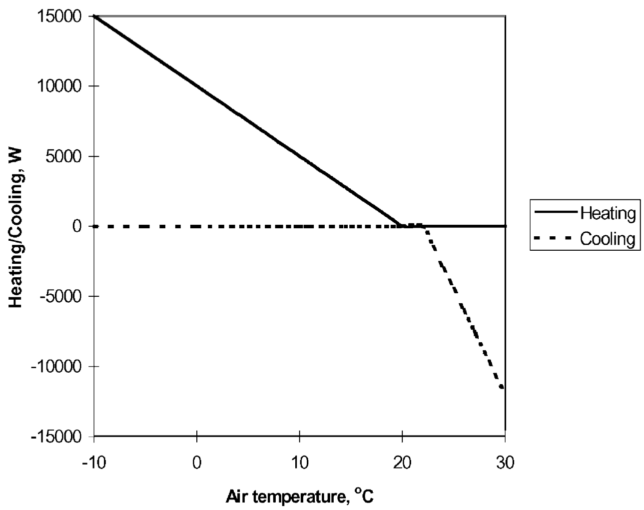

Fig. 3. Maximum heating and cooling as a function of temperature. In x-axis outdoor air temperature for heating and indoor air for cooling. Heating is reduced linearly as indoor temperature rises from 20 to 22°C.

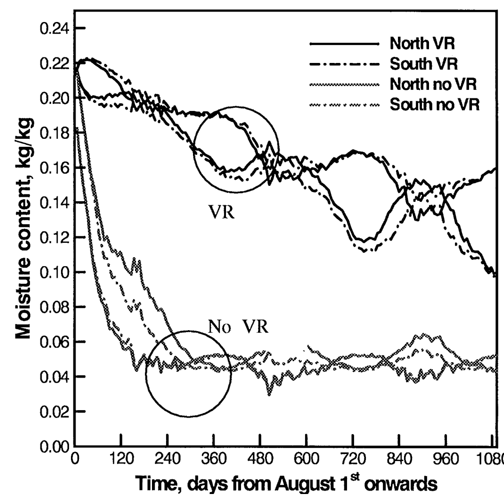

Fig. 5. Moisture contents at three depths of aerated concrete layer for North and South facing walls. Walls with 25 mm exterior EPS insulation.

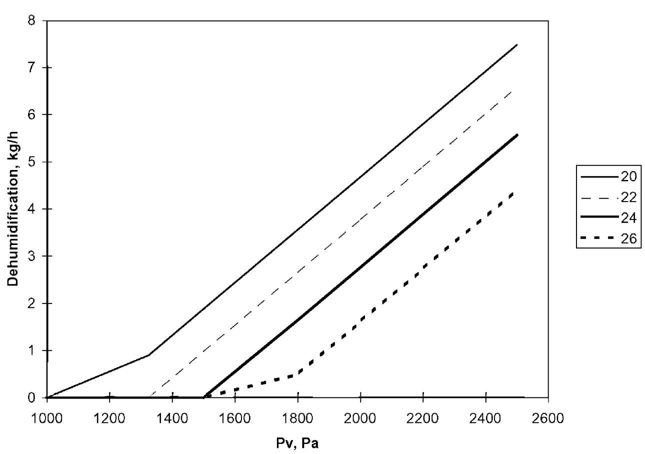

Fig. 4. Dehumidification as a function of interior air vapor pressure (x-axis) and interior air temperature (20–26°C, various curves).

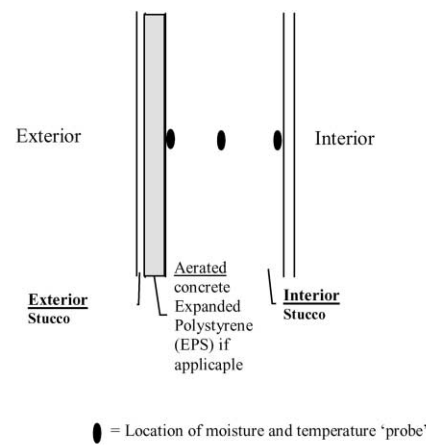

Fig. 6. The graphical layout of the parametric cases (Positioning of numerical moisture and temperature probes).

building was equipped with a heating and cooling system that turned on heating if the temperature decreased below 20°C and cooling if the temperature increased above 22°C.

Naturally in the climate of Miami the cooling demand is more prevalent. As the amount of cooling hours required in Miami is higher than that of heating, the cooling system had a drying effect on the indoor air if the relative humidity was above 50%. The dehumidifying effect was relative to the difference between vapor pressures in the indoor air and the reference vapor pressure (50% at room temperature). Fig. 4 shows the significant effect of dehumidification required for various interior temperatures and vapor pressures, it becomes evident that the climate of Miami is both hot and humid.

In Fig. 5, the moisture content in the wall systems as a function of time is presented to show the relative hygrothermal performance of the aerated concrete walls for two orientations (North and South) using two different vapor control strategies (with and without an interior vapor retarder). Results are shown for the wall systems that employed an exterior insulation of 25 mm expanded polystyrene. The simulations start from the first day of August (1961) for a period of three years. The three monitor points within the aerated concrete as depicted in Fig. 6 are plotted out. The slowest drying is exhibited by the wall that included the vapor retarder paint. Indeed the case that did not incorporate the vapor retarder dried to a moisture content of 0.05 nearly 8 times faster than the vapor retarder case. Minimal differences are observed between the south and north facing walls. As Miami is closer to the equator than say, Helsinki, north and south walls behave similarly because the solar angles (high), and the highest intensity of the sun per day comes to the east and west walls. From this figure, it becomes apparent that the preferred drying mode of this wall system in Miami is

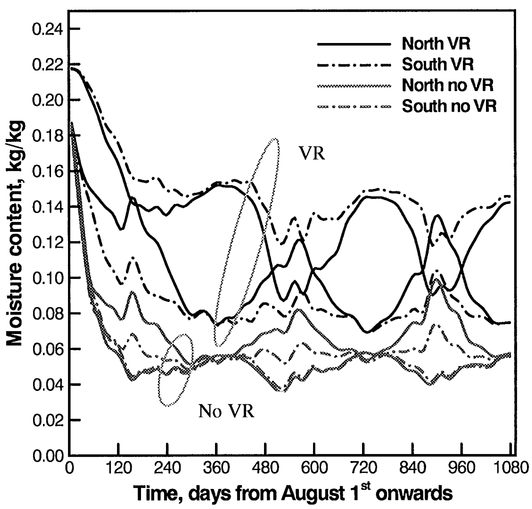

Fig. 7. Moisture contents at three depths of aerated concrete layer for North and South facing walls. Walls without exterior EPS insulation.

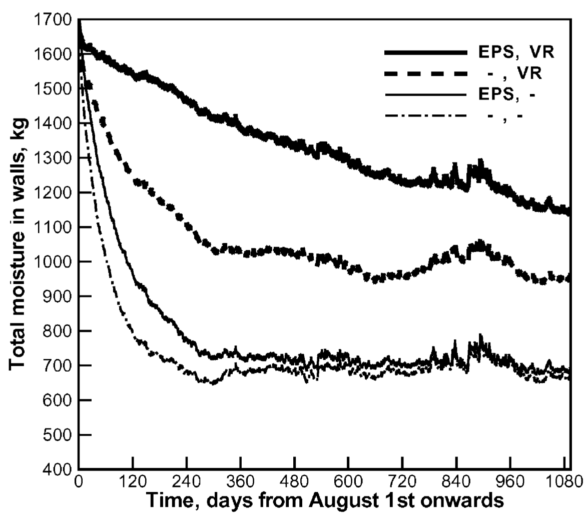

Fig. 8. Total moisture content in the building envelope as a function of time (starting from August 1st).

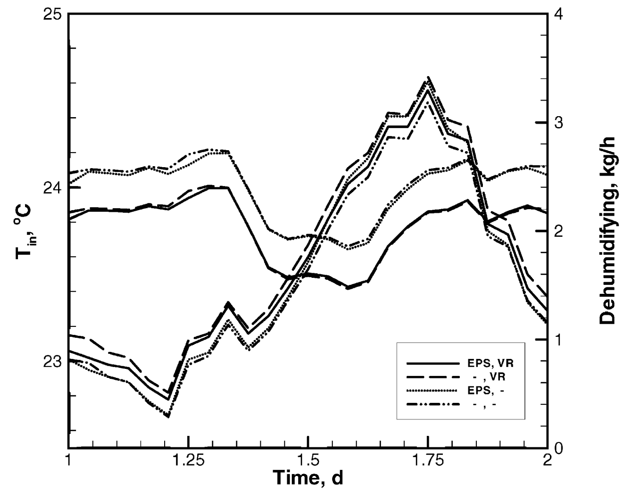

Fig. 9. Indoor temperature and dehumidification rate.

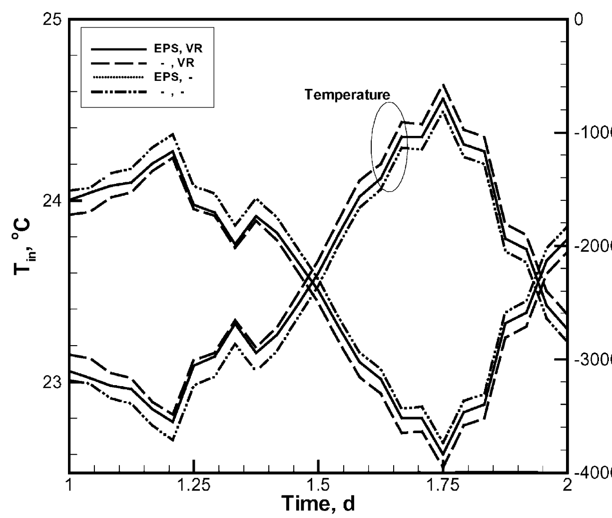

Fig. 10. Indoor air temperature and heating/cooling.

primarily towards the interior. However, for higher inside relative humidity, the drying potential of the overall wall system will be substantially reduced.

Fig. 7, shows similar building conditions, but without any exterior insulation. The same three monitor points within the aerated concrete as depicted in Fig. 6 are plotted out. The slowest drying is exhibited by the wall that included the vapor retarder paint. Indeed the case that did not incorporate the vapor retarder dried to a moisture content of 0.05 nearly 2.5 times faster than the vapor retarder case. Slightly higher differences are observed between the south and north facing walls, than the case with exterior insulation. Comparing Figs. 5 and 7, it becomes apparent that exterior insulation retards the drying performance of the building envelopes.

Fig. 8 depicts the transient total moisture mass present in the aerated concrete building as a function of time. Results are shown based on the wholistic moisture engineering approach described earlier in the paper. It is clear that the direct coupling of the interior environment and the building envelope parts can correctly represent the drying performance of the building. It is evident that interior vapor control and exterior insulation strategies for this particular building reduces the overall drying performance of the building. Furthermore, a significant amount of water is present in the building, which requires several years to dry out.

Figs. 9 and 10 show the interior temperature and dehumidification requirements for the building for a period of one day. Daily diurnal cycles are clearly shown, and a peak load for cooling and dehumidifying the building is depicted. Humid fresh supply air drawn into the building from the exterior dominates in the dehumidifying scene which can be seen clearly by comparing the cases with and without vapor retarder in Fig. 11. During the first of

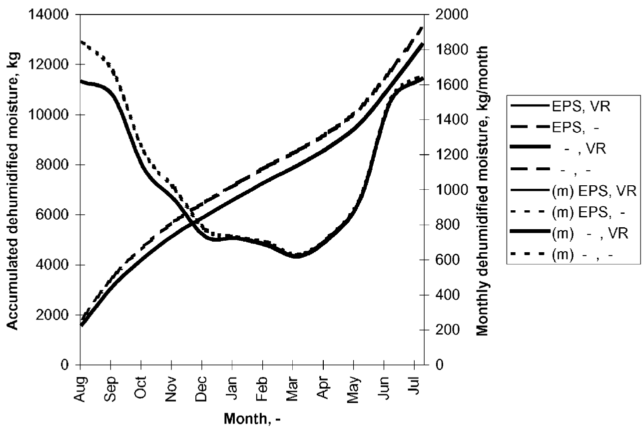

Fig. 11. Dehumidification of indoor air: accumulated and monthly (m) dehumidified moisture.

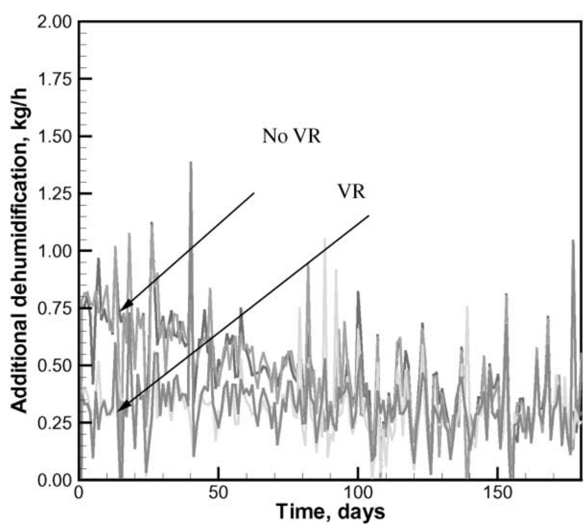

Fig. 12. The difference between the real dehumidification and the dehumidification of outdoor ventilation air to indoor air humidity. For cases with vapor retarding paint the difference is caused by interior moisture sources 6.1 kg/day = 0.25 kg/h on average.

August month the demand for dehumidifying is increased by approximately 20% due to moisture diffusion from the building envelope (inward drying).

Fig. 11 shows the dehumidification of indoor air, as a function of monthly amounts. Results show that the EPS insulation did not make any difference in the monthly averaged results. The simulation results for buildings that employed a vapor retarder are on top of each other, and similar results are demonstrated without the use of the vapor retarder. Fig. 12 presents the increase in dehumidification due to moisture flows from the walls into the indoor air. The capacity of the dehumidification device needs to be approximately 0.5 kg/h higher initially.

Fig. 13 shows the moisture flows through the interior surfaces of the walls into the indoor air of the building.

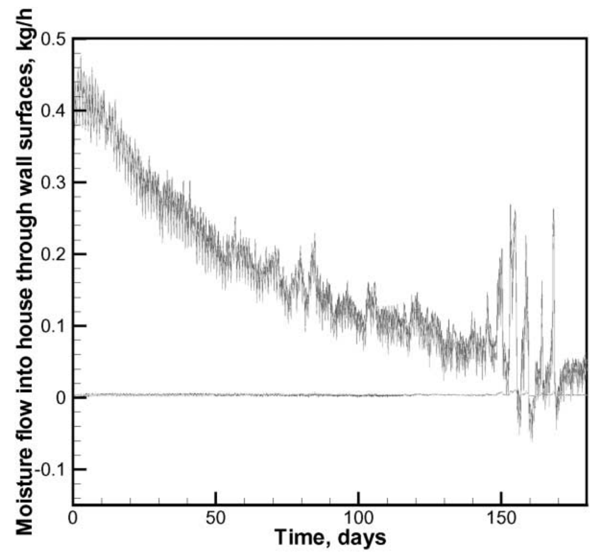

Fig. 13. Moisture flows into the building from the walls. Flat lines are for the vapor retarder cases and the decreasing curves for cases with vapor open interior surfaces.

It can be clearly seen that the moisture load is increased during the first half of the first year after construction.

9. Vapor control and fungal contamination in building envelope

Fungal spores are found in virtually every building. The composition of the air spora is a mixture of species which resembles that which is found in outdoor air. Depending on the ventilation and air conditioning practice, indoor counts may be lower. High level of fungal spores and mycoflora in indoor air is often a sign of moisture or water damage. Fungi are able to grow on a wide range of organic material, such as those used in constructions. Most common reasons for moisture damage and dampness problems in buildings are improper design, water leaks, defective drainage, inadequate ventilation, and moisture condensation from thermal bridging.

In Finland, Vahteristo et al. [16], reported that in moisture damaged rental apartments, inhabitants experienced respiratory symptoms and infections. Mycotoxins have caused serious health hazards, cancer and deaths [17]. A recent clinical epidemiological cluster in the Cleveland area of lethal hemorrhagic lung diseases in infants have focused attention on inhalation-related health risks of toxic fungi such as *Stachybotrys chartarum atra* [17].

In this paper, the risk for mold growth within the wall section was analyzed with the use of a mold growth prediction model embedded in the simulation model.

9.1. Estimation and description of mold growth analysis

Mold growth in the structures was estimated using a model equation that employs temperature, relative humidity and exposure time as input. The mold growth model and involved mathematical equations are presented in details in another paper by Hukka and Viitanen [18] and only short introduction is given here.

Quantification of mold growth in the model is based on the mold index used in the experiments for visual inspection. The mold growth model is based on mathematical relations for growth rate of mold index in different conditions including the effects of exposure time, temperature, relative humidity and dry periods. The model is purely mathematical in nature and as mold growth is only investigated with visual inspection, it does not have any connection to the biology in the form of modeling the number of live cells. Also the mold index resulting from computation with the model does not reflect the visual appearance of the surface under study, because traces of mold growth remain on wood surface for a long time. The correct way to interpret the results is that the mold index represents the possible activity of the mold fungi on the surface.

The model makes it possible to calculate the development of mold growth on the surface of small (currently only wooden) samples exposed to fluctuating temperature and humidity conditions including dry periods. The numerical values of the parameters included in the model are fitted for pine and spruce sapwood, but the functional form of the model can be reasoned to be valid also for other wood-based materials.

The calculation method is briefly as follows. The critical relative humidity above which mold growth is possible is a function of temperature. At temperature below 0°C and above 50°C mold growth is not possible. The critical relative humidity lies between 100%-RH (at 0°C) and 80%-RH (at 20°C). The growth rate of mold increases as temperature and relative humidity increase and it is also dependent on the mold index itself: higher mold index enables faster mold growth. During dry periods when relative humidity is below the critical humidity or when temperature is outside the range of temperature enabling mold growth the mold index decreases at a constant rate.

The mold index scale assumes the values in Table 1. The mold index will be interpreted in this paper as a risk for damage.

Table 1
Mold index values and their meaning

Index	Descriptive meaning
0	No growth
1	Some growth detected only with microscope
2	Moderate growth detected with microscope
3	Some growth detected visually
4	Visually detected coverage more than 10%
5	Visually detected coverage more than 50%
6	Visually detected coverage 100%

9.2. Mold growth results

Due to the inability to dry inwards the walls with vapor retarder have high risk for mold growth under the vapor retarder. The moisture contents stay at high level for several months (even years). Combined with the suitable temperature mold growth can easily be initiated in the walls. Fig. 14 shows the mold growth index behind the vapor retarder paint (or under vapor open paint) as a function of time.

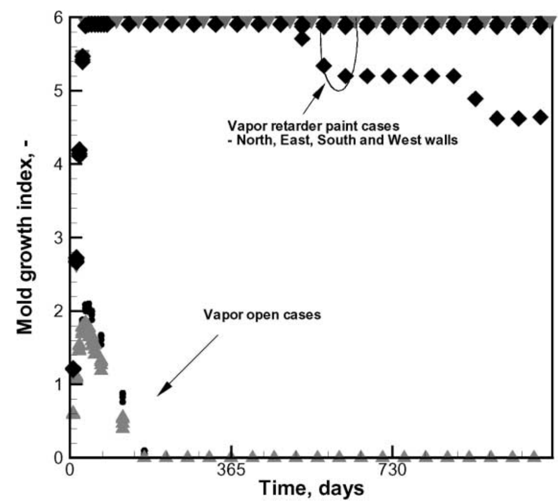

Fig. 14. Mold growth index on the interior surfaces (behind vapor retarder if applicable) of the walls with and without vapor control.

10. Conclusions

Vapor diffusion control and insulation strategies have a significant effect on the hygrothermal performance (drying potential) of aerated concrete wall block buildings in hot and humid climates. This study, which included the effects of vapor transport, liquid transport found that the use of a tight interior vapor control may not be beneficial to drying the initial construction moisture in hot and humid climates. The results showed slow drying even for the no-retarder case as the drying potential for climatic conditions of Miami are not very favorable.

Exterior insulation strategies applied in aerated concrete wall systems, have some thermal benefit but significantly reduce the drying performance of aerated concrete buildings with high initial construction moisture. Indeed, several years, 3–10 years depending on the parametric cases examined in this study may be required to dry out the initial moisture of the aerated concrete blocks in weather conditions of Miami. This may require that the interior finish (paint, wallpaper, wood, etc.) must have certain moisture properties or otherwise the interior surfaces may only be coated after the initial moisture has sufficiently dried out in order to avoid moisture related problems, such as mold growth, for example, that may appear after some weeks or even later after several months. The processes leading to these problems may have been initiated by the initial moisture.

The proper combination of interior and exterior vapor control and insulation control must be employed, as demonstrated in this study. If buildings are equipped with air conditioning equipment, moisture transport from the interior can be regulated. Additional research is needed to determine the critical range of interior climatic conditions that owners of the building must adhere to. Buildings, must be designed to accommodate some form of synchronized moisture control that utilizes drying towards the interior as well as the exterior. Aerated concrete walls that incorporate such features can be developed with substantially higher moisture load tolerances for any climatic region, without necessarily requiring special cavities or other expensive changes in design.

Today, by effectively employing wholistic moisture engineering analysis, integrating material properties, system and sub-system performances (lab and field studies) and advanced modeling building envelope systems can be optimally designed. Advanced hygrothermal modeling is an efficient means to develop engineered construction products, similar to other high-tech industries such as aerodynamics, automotive and even the electronic fields.

The results provided in this paper are only applicable to the specific materials, wall specifications and weather conditions employed. Further work is needed to characterize the effects of defects in the exterior surface or possible moisture infiltration or exfiltration from the interior or exterior environments.

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