Cyclic Temperature-Gradient-Driven Moisture Transport in Walls with Wetted Masonry Cladding

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ABSTRACT

This paper presents experimental results from the small-scale tests of the ASHRAE-1235 project on solar-driven vapor transport in wood frame walls. The objective of the tests is to produce precise measurements on wetting and drying behavior of internal parts of the back wall, when a wetted masonry cladding is loaded under cyclic temperature loading. The small-scale tests report wetting of the different wall components under constant and cyclic high temperature loading. It is found that, due to the temperature gradient, an important vapor flow is generated to the back wall, wetting the oriented-strand board (OSB) sheathing, mineral wool and gypsum board. The vapor permeance of the interior finishing determines the wetting of the gypsum board: a vapor tight vinyl wall covering leads to significant wetting of the gypsum board and very low drying rates during drying. A vapor open paint finishing reduces the moisture content of the gypsum board by a factor of 4 to 6. The magnitude of thermal loading determines the rate of wetting and drying. Hence, during cyclic loading, where the average thermal loading is lower than a constant high temperature loading, the wetting potential of the OSB and gypsum board reduces. With the lower thermal loading, the drying of the OSB and gypsum board is reduced which results in higher final moisture contents. The presence of a wood stud leads to lower moisture contents of the back wall for vinyl wall covering finishing, since the wood stud absorbs part of possible flow to the gypsum board. In the case of vapor open finishing, the hygroscopic behavior of the wood stud leads to higher moisture contents of the back wall.

INTRODUCTION

Over the last few decades, more and more attention has been given to moisture control in building envelopes. One aspect of moisture control that is still not completely understood and solved is the so-called solar-driven vapor movement. An instance of such movement happens when rain is absorbed by porous cladding such as brick veneer. Heating of the wet masonry due to solar radiation will induce inward water vapor flow, especially when the interior space is air-conditioned at lower temperature. These water vapor flows can be important and lead to moisture accumulation in the back wall. Sustained exposure to high moisture content may lead to the development of mold and rot growth, corrosion of fasteners and reduction of the thermal insulation value. The occurrence of inward moisture flow due to solar radiation is more prevalent in mixed and hot climates, but may also be observed during the summer in cold climates. To avoid such problems, the amount of moisture diffusing through an envelope must be reduced (Tsongas and Olson 1995) or allowed to dry out quickly (TenWolde 1989 and Sandin 1993).

The first mentions of summer condensation or condensation due to inward flow on vapor barrier sheets were in-situ observations. One of North America's premier building scientists, Neil B. Hutcheon (1953), clearly identified that *"Hot sun on a wetted outer withe can still drive water as vapour back into the inner withes, producing wetting by condensation there"*. Hutcheon recommended the use of ventilation cavities to promote air circulation providing drying conditions for both winter and summer seasons. Then, more observations from field testing were reported. Wilson (1965), TenWolde et al (1986) and Straube (2001) observed that moisture accumulation on the interior side of assemblies occurs in constructions

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Table 1. Vapor Permeance and Equivalent Vapor Resistance Thickness of Some Materials

	RH	Vinyl Wall Covering (VWC)	Acrylic Paint	Gypsum Board	Oriented-Strand Board (OSB)	Spun-Bonded Polyolefin (SBPO)	Building Paper (BP)
Thickness (mm)		0.13	0.1	12,5	8.75	0.15	0.34
Density (kg/m^3)				850	550		
Equivalent vapor resistance thickness (m)	0.33	8.24	0.256	0.126	2.46	0.058	0,097
	0.7	3.92	0.113	0.095	2.22	0.058	0.061
	0.91	3.37	0.047	0.068	0.31	0.058	0.045
Permeance (ng/m².s.Pa)	0.33	24	756	1537	79	3330	1990
	0.7	49	1717	2042	87	3330	3180
	0.91	58	4128	2861	626	3330	4310
Permeance (perms)	0.33	0.4	13.3	27.0	1.4	58.4	34.9
	0.7	0.9	30.1	35.8	1.5	58.4	55.8
	0.91	1.0	72.4	50.2	11.0	58.4	75.6

with vapor barriers. It has also been observed that different sheathing materials influence the vapor flow through assemblies (Straube and Burnett 1995, and Salonvaara et al 1998). Sherwood (1985) conducted a series of field tests on several different wall panel constructions for two years in a hot, humid climate. During the summer months, with outdoor average temperatures reaching upwards of 100ºF, south facing walls resulted in higher moisture content increases compared to northern exposed walls. Also, work aimed at studying cladding ventilation provided some information. Straube and Burnett (1998), in a field test, concluded that ventilating the air space can further improve enclosure drying, and thus decrease the occurrence of inward condensation. Pressnail et al (2003) concurred with Straube and Burnett using a small-scale test. So far, most of the work done aimed at reporting the occurrence of inward moisture movement due to the high temperature gradient.

However, the phenomenon of cyclic vapor flow driven by solar radiation and the influence of the wall composition on the hygrothermal performance and durability of wall systems subjected to such flow are not yet fully understood. The ASHRAE T.C. 4.4 committee identified this need, and a research project was initiated to develop fundamental understanding of the impact of solar-driven moisture flow. This paper presents the small-scale experimental setup and reports on the results for various wall assemblies for this ASHRAE funded project. Two other experimental parts are also underway: laboratory large-scale testing under controlled loading conditions and field testing in Charleston, SC. The results from the three experimental parts will be used to validate computer models, which will be subsequently used to simulate more variations of assembly constructions and environmental loading conditions.

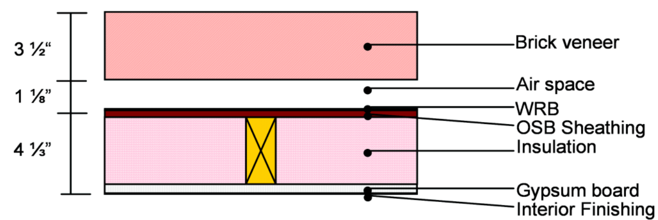


Figure 1 *Composition of the wood-frame wall with brick veneer.*

EXPERIMENTAL PROCEDURE

A small-scale testing setup was developed and built to test simultaneously eight 400 mm x 400 mm specimens. The wall composition is typical for North American low-rise residences, insulated with fiberglass insulation between the studs. A typical cross-section is given in Figure 1. An air cavity is present between the brick veneer and the back wall. An exterior sheathing of oriented-strand board (OSB) is used. Two types of weather resistive barriers (WRB) on the OSB are considered: spun-bonded polyolefin (SBPO) and building paper (BP). On the gypsum board, two different finishings are used: a two-layer acrylic paint and a vinyl wall covering (VWC).

The indoor and outdoor conditions aim at representing summer conditions in Charleston, South Carolina, including solar radiation on the outside cladding and conditioned air at the indoor side.

Material Properties

In Table 1, the equivalent vapor resistance thickness and permeance of some materials are summarized, where permeance is defined as vapor permeability divided by thickness and equivalent vapor resistance thickness represents the thickness of an air layer with equivalent vapor resistance. These data come from own measurements for VWC or literature published by Roels et al (2006) for acrylic paint and gypsum board, Kumaran et al (2006) for OSB and DuPont (2006) for SPBO and BP. We observe that vinyl wall covering has a very low permeance compared to the acrylic paint. Gypsum board is highly permeable, while OSB is rather vapor tight at low RH and more open at the higher RH's observed during the test. Both SBPO and building paper have a comparable high permeance at high RH.

Small-Scale Experimental Setup

Test Setup. The small-scale setup consists of eight horizontal specimens on a table frame (Figure 2a). A hot box covers the specimens providing either constant or cyclic outside boundary conditions (Figure 2b). The short sides of the support table are open to the laboratory allowing conditioned air (constant temperature and RH) to flow below the specimens. The hot box is heated by a closed-loop heating system, comprising a heating chamber equipped with eight 250W infrared lights and a fan. The system is regulated by a thermostat. The 15 ¾ in. (0.4 m) x 15 ¾ in. (0.4 m) specimens are constructed within an insulated vapor tight Plexiglas frame ensuring one-dimensional heat and moisture flow. Three different wall parameters are investigated: weather resistive barrier, interior finishing and inclusion/absence of a wooden stud.

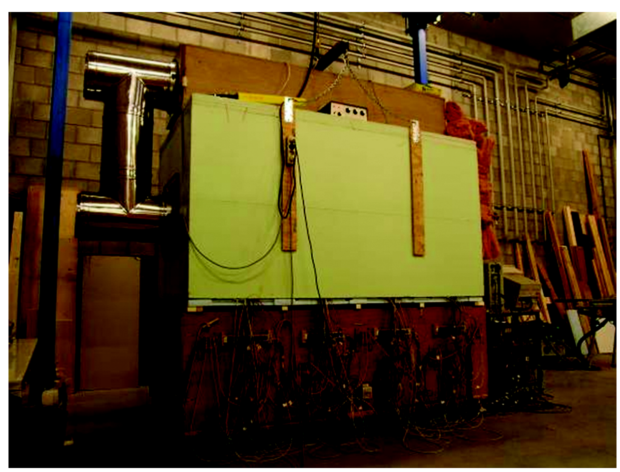
Test Protocol. At the beginning of the test, 1.5 liter of water is spread over the masonry leading to an average moisture content of 110 kg/m, which is half of the capillary saturation moisture content.

The experiment is divided into two periods: a wetting period and a drying period. During the wetting period, the masonry remains covered with an aluminum plate, sealed with a gasket, preventing drying of the masonry towards the outdoor environment. The drying period starts after 17 days by removing the aluminum plates from the specimens, allowing drying both towards the indoor and outdoor environment.

Two test conditions are considered: constant outside temperature loading and cyclic temperature loading. For the constant loading experiment, the outside temperature is 104ºF (40ºC) and an outside relative humidity (RH) of 10 %. For the cyclic loading an outdoor temperature loading of 104ºF (40ºC) during 8 hours is followed by 16 hours at 70ºF (21ºC) (see Figure 3). The outdoor relative humidity varies between 10 % RH at high temperature and 50 % RH at low temperature following the temperature loading. A constant temperature of 64.5ºF (18ºC) and 50% RH is used as the indoor climate.

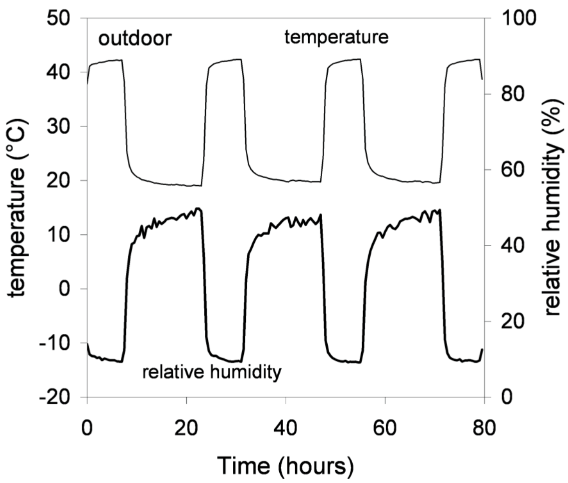
Moisture Content Determination by Gravimetry. The moisture content of the different parts of the wall is determined by gravimetry with a balance with an accuracy of 0.1 grams. The three parts - brick veneer, sheathing (OSB + WRB), insulation (+ eventually wooden stud) & gypsum board (+ interior finishing) are weighed individually, as shown in Figure 4. The brick veneer and the insulation and gypsum parts are tightly fit within an acrylic frame; a neoprene gasket is placed between the two frames to ensure excellent airtightness between measurements. The number of measurements was limited to twice a week for the first 45 days and once a week for the remainder of the experiment in order not to disturb the samples too much. At the end of the experiment, the individual materials are oven-dried at 122ºF (50ºC) to obtain their dry weights. The determination of the individual weights of all materials, which involves a complete dismantling of the entire assembly,

(a)

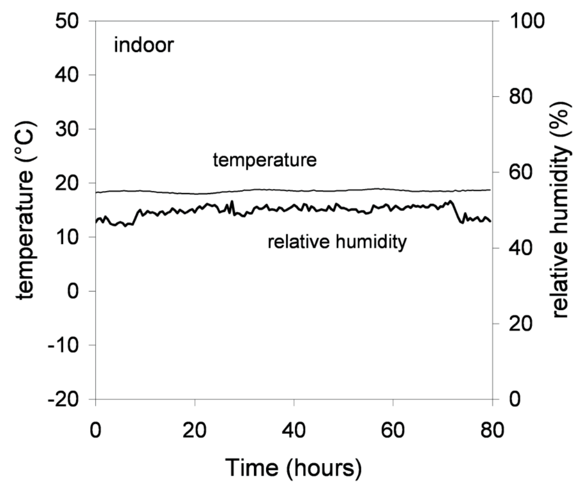


(b)

Figure 2 *(a) Test specimens on table frame (the aluminum plates are removed from the specimens), and (b) hot box above table frame (the heating chamber is situated on top of the hot box).*



(a)



(b)

Figure 3 *Temperature and RH variation for the cyclic test: (a) outdoor and (b) indoor.*

is done four times over the course of the experiment: initially when the materials are first assembled before the wetting phase, between the wetting and drying phases, at the completion of the drying phase and once the materials are oven-dried.

Continuous Measurements. The temperature, relative humidity and moisture content are electronically monitored throughout the entire duration of the experiment at various positions within the test specimens. The temperature is measured by gauge 26, type T (copper/constantan) thermocouples and relative humidity sensors equipped with a temperature sensor. The relative humidity is monitored using capacitive RH sensors with an accuracy of 3% in the 0-95%RH range. The moisture content in the wooden studs and the sheathings is monitored using electric resistance moisture content probes, the output measured using a Delmhorst transducer.

RESULTS

Test results of the small-scale experiments for constant and cyclic loading are reported in this paper. The results give the moisture content evolution (in kg/m or in kg/m) for the different parts. The moisture content in kg/m is used when we describe the moisture content of the total specimen or for the wall specimen with wood stud. The moisture content in kg/m is used when we present the moisture content of one of the parts of the specimen (without wood stud). The moisture content of masonry (part 1) is the average moisture content of brick and mortar joints, and no distinction will be made between the two components. The moisture content of part 2 is primarily the moisture in OSB, since the moisture present in the WRB is small and can be neglected. For part 3 without wood stud, the moisture present in the insulation or interior finishing is small compared to the moisture present in the gypsum board. Therefore, we may consider the moisture present in part 3 as the moisture content of the Gypsum Board.

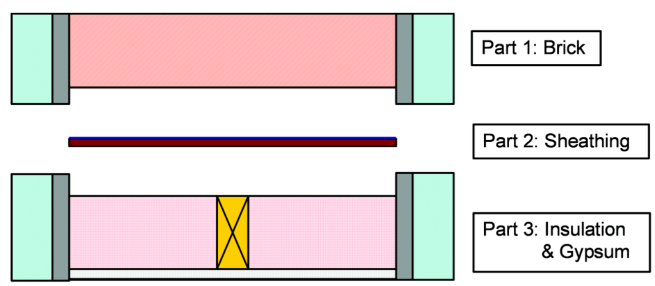
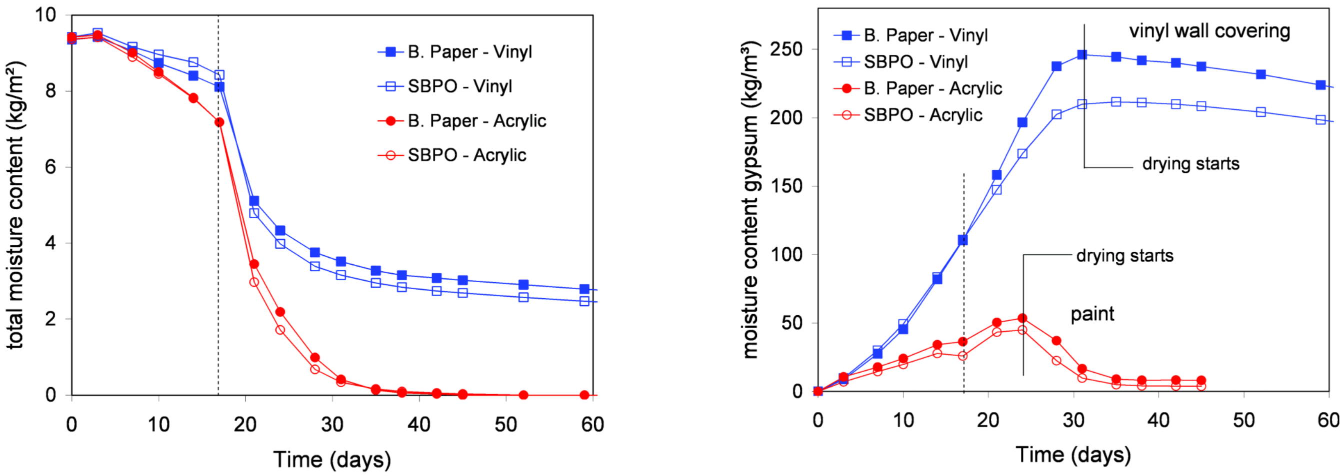


Figure 4 *Small-scale assembly parts.*

Constant Outdoor Environmental Conditions

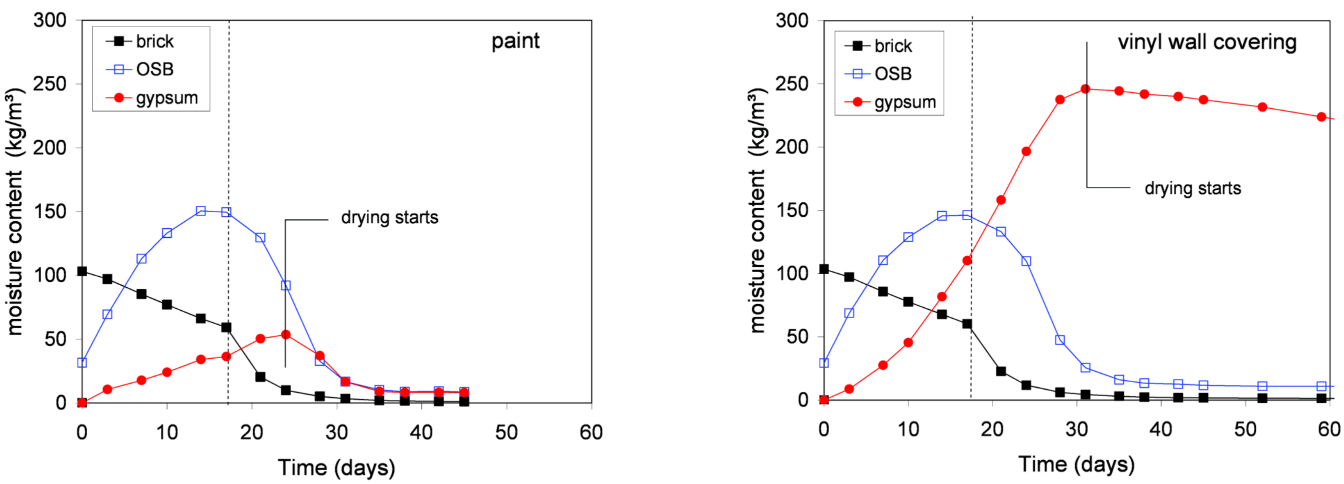
Global Observations. Figure 5a gives the evolution of the total moisture content for all variants without wood stud during the wetting and drying phases. We first observe a distinct behavior of the wall specimen during wetting period (slow moisture decrease) and drying period (fast moisture decrease). We will discuss these two phases in detail separately in the following sections. In Figure 6b, it is shown that there is a different moisture behavior of the gypsum board dependent on the finishing of the gypsum board. Moisture uptake during the wetting phase by the gypsum board covered with the vapor tight vinyl wall covering is much higher than the uptake of moisture by the gypsum board with vapor open paint. The type of WRB does not influence significantly the moisture behavior of the gypsum board, as both materials have similar permeance at high relative humidities.. Even in the case of paint finishing, the moisture content of the gypsum board is very high (maximum of 50 kg/m, which corresponds to a RH value of 96 %, Roels et al 2006).

Wetting Phase. During the wetting period (left of the dashed line), moisture transport to the outdoor environ-



(a) (b)

Figure 5 *Moisture content evolution for constant loading conditions: (a) moisture content (kg/m^2) for the total specimen (comparison between VWC and paint finishing), and (b) mositure content (kg/m^3) evolution of gypsum for different interior finishing.*



(a) (b)

Figure 6 *Moisture content evolution of different components for constant loading conditions: (a) paint and (b) vinyl wall covering.*

ment is prohibited by the presence of aluminum plates. Moisture is driven by the temperature gradient from the wet masonry to the back wall and to the inside environment. The total moisture content in the specimen decreases slowly (Figure 5a). Vapor flow to the inside environment remains low.

Figures 6a and 6b show that moisture is taken up by the OSB and the gypsum board. The moisture uptake by OSB first increases fast, but finally attains a maximum value of 150 kg/m^3, which refers to a RH value of 98 % (the capillary moisture content of OSB is 260 kg/m^3). The curves do not differ for the vinyl wall covering and paint finishing of the gypsum board.

Drying Phase. During the drying phase, when the aluminum plates are removed and masonry can dry to the outside, we observe that the total moisture content decreases fast in a first stage (Figure 5a). Figures 6a and 6b show that the fast drying in the first stage can be attributed mainly to the drying of the masonry.

In a second drying stage, Figure 5a shows that the drying of the wall with vinyl wall covering is prohibited. The moisture content of this wall remains at high level, while the wall with paint finishing dries out totally. To analyze this different behavior in more detail, we first observe in Figures 6a and 6b that there is no large difference in drying of the masonry and the OSB sheathing for paint and vinyl wall covering. A major difference is found in the moisture behavior of the gypsum board finished with vinyl wall covering and paint. The gypsum board with vapor tight vinyl wall covering continues to take up moisture during the drying phase, and only starts to dry when the masonry and OSB are totally dried out. On the other hand, the vapor open paint, which first limits the wetting of the gypsum board, secondly also allows a fast drying to the inside environment. The gypsum board with paint starts to dry even when the OSB is still wet. This means that the flow of moisture due to the thermal gradient from the wet masonry and OSB to the gypsum board is lower than the flow from the gypsum board to the indoor environment. This highlights the importance of the vapor permeability of the finishing of the gypsum board. Figures 6a and 6b show also that the type of weather resistive barrier, in this test, does not change substantially the wetting and drying behavior of the OSB and gypsum board.

We finally remark that in these (severe) tests with constant boundary conditions, the moisture contents of OSB and gypsum board remains too high in all cases regarding moisture related damage problems. Therefore, the test results of more realistic cyclic boundary conditions are discussed in the next section.

Constant Versus Cyclic Outdoor Environmental Conditions

Figure 7a-d compares the moisture behavior of the walls for constant and cyclic environmental conditions. The major

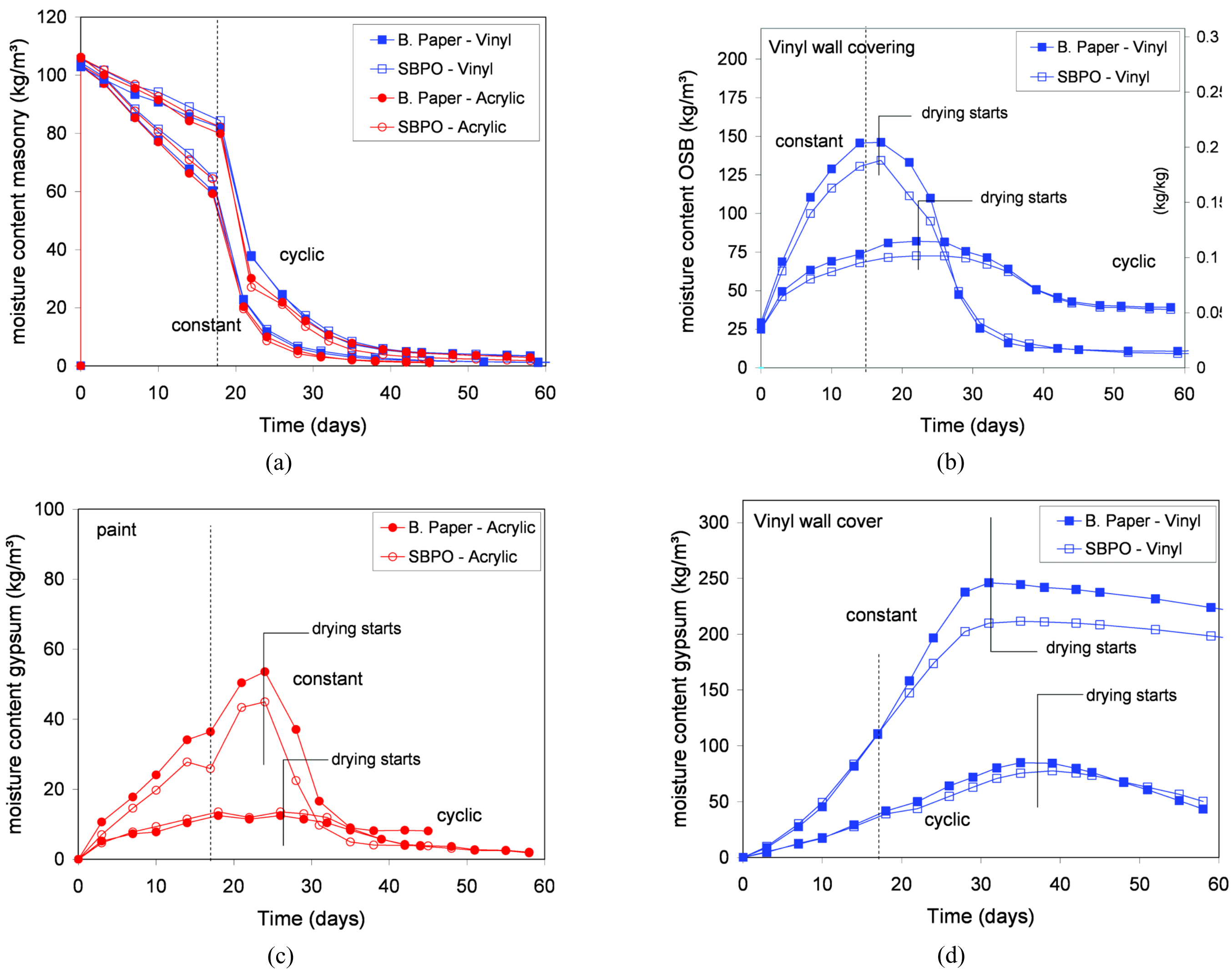


Figure 7 *Comparison of moisture content evolution for constant with cyclic loading conditions: (a) moisture content of masonry for all variants of WRB and finishing of the gypsum board, and (b) moisture content of OSB for the VWC finishing. The results for paint finishing do not differ much: (c–d) moisture content of gypsum board for (c) paint and (d) VWC finishing.*

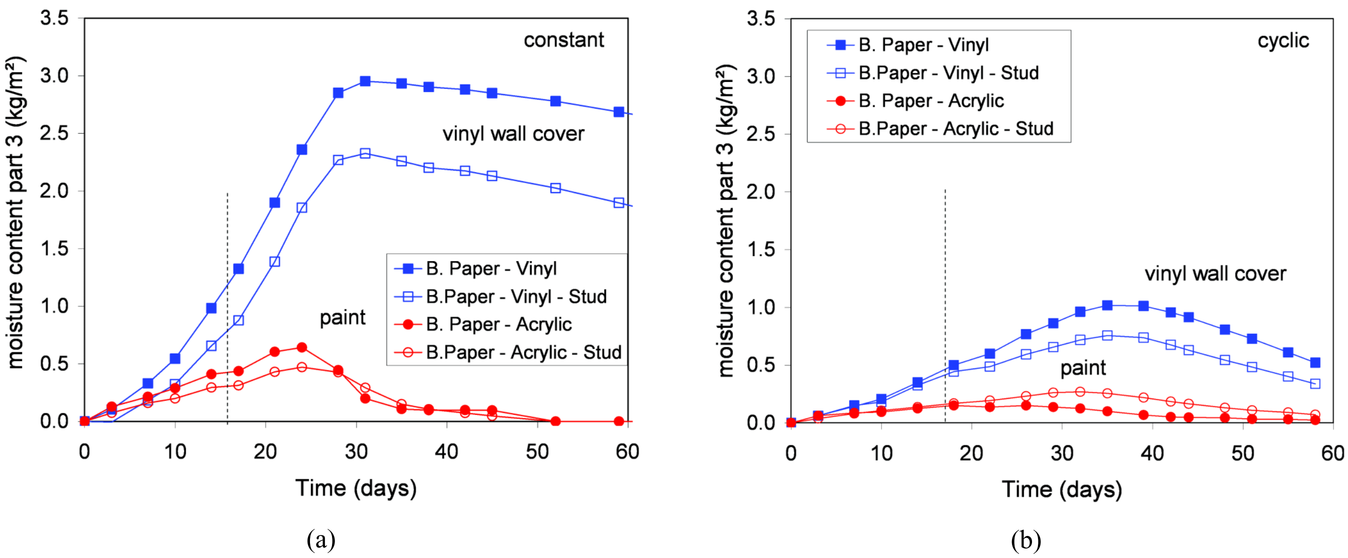


Figure 8 *Moisture content (kg/m^2) evolution of part 3 of the back wall (insulation + wood stud + gypsum) for different interior finishing (vinyl wall covering and paint): (a) constant outside loading conditions and (b) cyclic loading conditions. The open symbols represent the wall with wood stud; the solid symbols represent the symbols without wood stud.*

difference is that, during cyclic loading, the global thermal loading, which is the driving force for the moisture transport from the wet masonry to the back wall, is reduced.

In Figure 7a, we observe that the decrease of moisture content of masonry during the wetting period (when the aluminum plate prohibits flow to the outdoor environment), is slower for cyclic conditions compared to the constant boundary conditions. The reduction of the thermal loading also leads to a slower drying of the masonry during the drying phase.

The cyclic thermal loading also leads to a reduction of moisture uptake by the back wall components during the wetting period (Figures 7b-d). Figure 7b shows that the moisture content of OSB during cyclic loading behavior not only remains lower compared to the constant boundary conditions, but also that the moment at which drying of the OSB starts is delayed and the rate of drying is slower, resulting in higher final moisture contents. This means that, during cyclic loading, the wetting and also the drying potential reduces and the materials remain, on average, for a longer time at higher moisture content levels.

For gypsum board, we observe a similar, but also distinct behavior: the wetting of gypsum board during cyclic loading is reduced and the start of drying is delayed, but the moisture content of the gypsum board remains in absolute values much lower than the ones observed for the constant conditions. The maxima of moisture content of the gypsum board with vinyl wall covering and paint in the constant loading case are respectively 230 versus 50 kg/m^3, or a ratio of 4.6 to 1. In the cyclic loading case, the maxima are respectively 81 versus 13 kg/m^3, or a ratio of 6.4 to 1. We may conclude that, although the absolute values of moisture content of gypsum board are higher for constant loading conditions, the wetting of gypsum board is relatively more severe in cyclic loading. We however remark that a maximum of 81 and 13 kg/m^3 for gypsum board with paint finishing refers to a RH of respectively 98% and 86%, which is still very high.

Finally, we observe that the moisture behavior of OSB and gypsum board does not depend much on the type of WRB in either the constant or cyclic loading case. Walls with SBPO show somewhat lower moisture contents of OSB and gypsum board than walls where building paper is used.

Presence of a Wood Stud

We investigate now the influence of the presence of the wood stud on the moisture behavior of part 3 of the back wall, consisting of a wood stud, gypsum board and insulation. Since the wall composition is not uniform, we present the results in kg/m^2 and not kg/m^3.

Before presenting the results, we discuss three issues to be considered: (1) wood is a hygroscopic material and will take up water vapor. When water vapor is driven from the masonry to the back wall due to the presence of the temperature gradient, also part of the water vapor transported will be taken up by the wood stud. The flow to the wood stud is essentially two-dimensional. In the drying phase, moisture in the wood stud has to dry out to the outside or inside environment. In the case of the vaportight vinyl wall covering, the wood has to dry out mainly to the outside environment, which can only occur when the OSB is sufficiently dry; (2) the wood stud will introduce a thermal bridge, changing locally the thermal gradient, and, probably, locally reducing the thermal gradient driven vapor transport; (3) due to the low vapor permeability of wood compared to mineral wool, the wood stud will reduce the possible vapor transport from masonry to the gypsum board. Based on these three considerations, we may conclude that the presence of a wood stud can result in a reduction of the possible flow to the gypsum board as well as a moisture uptake by wood leading to an increase of the total moisture content of part 3.

Figure 8a-b present the results of the total moisture present in wood stud, mineral wool and gypsum board (in kg/m^2). It should be noted that the y-axis scaling is the same for both figures. For the wall with vapor tight vinyl covering, we see that the presence of the wood stud results in a reduction of the total moisture content. For the wall with vapor open paint, the influence of the wood stud is small or even results in an increase of the total moisture content. This means that when the gypsum board has a vapor tight finishing, the wood stud primarily blocks the possible vapor transport. The contribution to the increase of total moisture content due to hygroscopic loading of the wood is relatively limited. In case of a vapor open finishing, moisture can easily leave part 3 of the wall through the gypsum board and the built up of moisture of part 3 will be influenced by the hygroscopic loading of the wood stud.

CONCLUSION

This paper presents experimental results from the small-scale tests of the ASHRAE-1235 project on solar-driven vapor transport in wood frame walls. The objective of the tests is to produce precise measurements on wetting and drying behavior of internal parts of the back wall, when a wetted masonry cladding is loaded under cyclic temperature loading. The walls are constructed according to typical North American construction practices, with vapor open mineral wool as insulation material between the studs. In the presented small-scale tests, eight horizontally placed specimens with different weather resistive barrier (SBPO and building paper), interior finishing (vapor tight vinyl wall covering and vapor open paint), with and without wood stud are exposed to a constant or cyclic varying outside thermal loading. The inside loading is constant and at lower temperature.

The small-scale tests show that, due to the temperature gradient, an important vapor flow is generated to the back wall, wetting the OSB, mineral wool and gypsum board. Moisture uptake by the gypsum board covered with the vapor-tight vinyl wall covering is much higher than the uptake of moisture by the gypsum board with vapor open paint. Vapor open paint finishing reduces the moisture content of the gypsum board up to a factor of 4 to 6.

The magnitude of thermal loading determines the rate of wetting and drying: during cyclic loading, showing on average a lower thermal loading, the wetting of the OSB and gypsum board reduces. Also, as a result of the lower thermal loading, the drying of the OSB and gypsum board reduces resulting in higher final moisture contents.

It was shown that, for the constant and cyclic loadings of the test, the type of weather resistive barrier does not change substantially the wetting and drying behavior of the OSB and gypsum board.

The presence of a wood stud leads to lower moisture content of the back wall for vinyl wall covering finishing, since the wood stud absorbs partly possible flow to the gypsum board. In the case of vapor open finishing, the hygroscopic behavior of the wood stud leads to higher moisture contents of the back wall.

In the (severe) tests with constant boundary conditions, the moisture content of OSB and gypsum board are too high in all cases producing moisture related problems. In the cyclic loading with vapor open paint, which is the less severe case, the maximum moisture content for gypsum board is still 13 kg/m^3 and for OSB 80 kg/m^3 which respectively equals to relative humidity of 86% and 90%. In both cases, ventilation of the air space was not included to better understand the role and impact of the interior finish material.

While the tests and analyses are ongoing, we hope that we have at least met some expectations of the reader, whereby we point out the existence of solar driven vaportransport and the possibility of severe moisture damage when a vapor tight finishing of the gypsum board is applied. We showed that, even with vapor open interior finishing and more moderate thermal loading, problems may arise and wall compositions have to be optimized. In further progress of the project, the experimental results, including the presented small-scale tests and the on-going large-scale tests and field measurements, will be simulated and the simulation models will be validated and used for further analysis under different yearly climatic loading.

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