Inward Vapor Drives in Adhered Veneer Wall Assemblies with Continuous Exterior Insulation

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ABSTRACT

Typical adhered veneer applications apply thin masonry units over a bed of lath-reinforced mortar over a sheathing membrane layer (often a single layer of building paper, felt, or housewrap). When used over wood- or steel-framed walls, numerous moisture problems and failures have been reported, in part due to inward vapor drives. One solution proven during field testing of full-scale wall specimens is the use of a vapor-impermeable membrane and air gap behind the adhered veneer (Straube et al. 2009). This paper describes an alternate solution using continuous exterior foam plastic insulation. For adhered veneer wall assemblies, the addition of continuous extruded polystyrene (XPS) on the exterior of the framing may prevent inward vapor drives, while meeting current and future codes, without the additional water management detailing of an air gap membrane. A set of full-scale wall assemblies were tested over a period of three years using a natural exposure facility in Midland, Michigan (International Energy Conservation Code climate zone 5). Results showed that the walls with continuous exterior insulation had fewer signs of moisture durability risk resulting from inward vapour drives compared to walls with direct applied veneer and (1) building paper (2) lower permeance sheathing membranes.

INTRODUCTION

Adhered veneers, in which masonry units are directly attached to a substrate via mortar and ties without a drainage or ventilation gap, have become a very popular finish in residential and light commercial construction. Typical applications apply thin masonry units over a bed of lath-reinforced mortar over a sheathing membrane layer (often a single layer of building paper, felt, or housewrap).

Numerous moisture problems and failures have been reported when adhered veneers are used over wood- or steel-framed walls (Rymell 2007). Warm-weather inward vapor drives and the lack of a well-defined drainage space have been implicated as the reasons for these moisture problems.

Drainage can easily be provided by installing a second layer of building paper, particularly if one layer is a creped housewrap, and ensuring that flashing and weep holes are included. However, controlling inward vapor drives is more problematic, as building papers and housewraps are typically highly vapor permeable, and both the mortar and the masonry unit can store a significant amount of rainwater via capillary absorption. During sunny weather following rain, water stored in the masonry can be driven into the sheathing and into the stud bay as vapor, resulting in wood decay and condensation on air-conditioned interior surfaces. Air-conditioned buildings with low-permeance vapor retarders to the interior (such as polyethylene, vinyl wall paper, and aluminum foil) exacerbate this problem.

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One solution proven during field testing of full scale wall specimens is the use of a vapor-impermeable membrane and air gap behind the adhered masonry veneer (Straube et al. 2009). However, this solution does not use continuous exterior insulation, and does require some additional detailing at penetrations and edges. Current and future building codes will require increasing the R-value of the wall assembly, and one of the best strategies is continuous exterior insulation. It has already been shown extensively, both in field studies and using building science principles, that exterior continuous insulation can result in improved moisture related durability for enclosure systems in cold climates by increasing the temperature of the structure, and potential condensation plane (usually the interior surface of the exterior sheathing). The addition of continuous extruded polystyrene (XPS) on the exterior of the framing may also be a successful strategy for avoiding inward vapor drives, while meeting current and future codes, without the additional water management detailing of an air gap membrane.

EXPERIMENTAL PROGRAM

An experimental program was developed to measure and compare the performance of adhered masonry veneer cladding using three methods of construction in a test hut in Midland, MI. Midland is in International Energy Conservation Code (IECC) climate zone 5. The full wall assembly details are discussed later in the report. The three construction methods are:

1. Typical direct applied masonry with building paper sheathing membrane.
2. Construction with lower permeance sheathing membranes.
3. Construction with continuous XPS insulation.

The objective of the study was to compare the moisture related performance of the wall assemblies with respect to inward vapor drives.

The test hut is approximately 11.6 m x 11.6 m (38 ft x 38 ft) with seven openings on each orientation measuring 1.2 m (4 ft) in width and 3 m (10 ft) in height. This allows the simultaneous testing of six different full scale wall systems on the North orientation (with the entry door) and seven full scale wall systems on the other three orientations. The test hut also has the capability to instrument the assemblies on all four corners of the hut. There are approximately 700 sensors measuring a combination of relative humidity, temperature and wood moisture content in all of the test assemblies. Only three walls on each orientation will be analyzed within the scope of this study.

Instrumentation

Each of the test walls was outfitted with a series of temperature, relative humidity (RH), and wood moisture content sensors. These sensors were continuously monitored at given intervals and recorded throughout the testing period using a data acquisition system. Photographs of the individual sensors are shown in Figure 1 and Figure 2.

Wood moisture content sensors were installed in the sheathing of the comparison walls that were constructed with OSB sheathing, and a surrogate wood wafer with moisture content pins was installed directly against the XPS in the exterior-insulated comparison wall. This allows measurement at the same depth through the assembly for wall-to-wall comparison. Where wood-based measurements were recorded, wood moisture contents were determined from the electrical resistance of wood, based on the Garrahan equation (Garrahan 1988; Onysko et al. 2010). The wood moisture content pins were installed in combination with a temperature sensor in all locations to allow for temperature correction.

FIGURE 1: Sheathing MC/T and Cavity Space RH at Mid-Depth and Interior Temperature-Only Sensor for Walls 3a and 3b

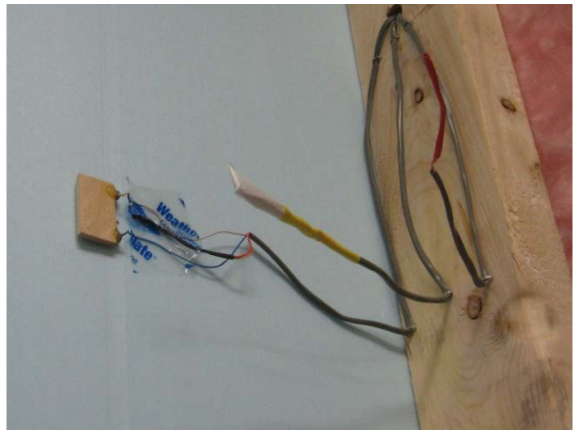

FIGURE 2: Wood MC Wafer against XPS, Cavity Space RH at Mid-Depth and Interior Temperature-Only Sensor for Wall 3C

Relative humidity sensors were installed at the mid-depth location of the stud cavity at an upper and lower location in the stud cavity. Relative humidity sensors were always installed in combination with a temperature sensor, both of which are protected by a vapor permeable, water resistant cover. Thermistors were also installed on their own in several locations to determine the temperature profile through the wall assembly.

Boundary Conditions

Determining and recording both the interior and exterior boundary conditions is critical to analysis, as enclosure performance will be related to the hygrothermal gradients imposed across the assembly from both the interior and exterior.

Exterior Boundary Conditions. To monitor the local exterior boundary conditions, a weather station was installed on the roof of the test facility. The monitoring system continuously collects weather data including: ambient air temperature and relative humidity, wind speed and direction, rainfall, and solar energy. It is important to have on-site weather information for any necessary comparison and correlation with the analysis data.

Interior Boundary Conditions. The interior boundary conditions of this study are limited to the interior relative humidity and temperature as shown in Figure 3. One intentional wetting was conducted during the analysis period as identified in the analysis section, but analysis of the intentional wetting event was not included in the scope of this study.

The temperature was controlled at approximately 22°C (72°F) for the entire test period. Some peaks in the temperature occurred during testing when there were some difficulties controlling the HVAC equipment. The interior RH setpoint was approximately 28% in the winter months, although the interior relative humidity was difficult to control during the third winter because of the addition of pressurization to the hut using exterior air. The interior RH ranged between 40% and 50% during the summer months for the first three years. Four ceiling-mounted fans constantly circulated air inside the space to limit temperature and humidity variances in all areas of the hut.

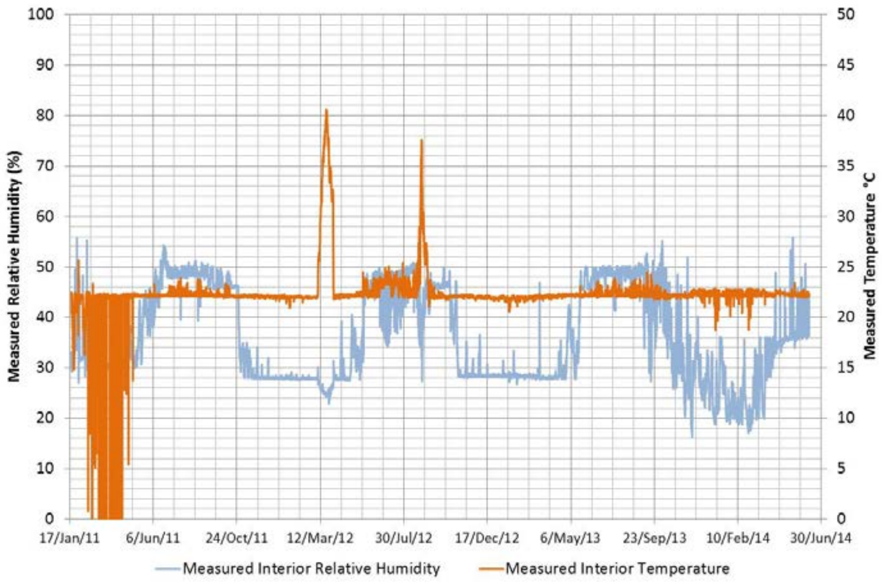

FIGURE 3: Interior Boundary Conditions

Wall Assemblies

The three comparison walls for this analysis were constructed on all four orientations of the test hut and are described in Table 1 below.

Wall	Interior Finish	Vapor Control	Framing	Cavity Insulation	Sheathing	Sheathing Membrane	Cladding
3a	13 mm painted gypsum board	Polyethylene (Class I)	2x4	R11 fiberglass batt	OSB	2 layers #15 felt	Adhered stone veneer /vinyl siding
3b	13 mm painted gypsum board	Polyethylene (Class I)	2x4	R11 fiberglass batt	OSB	Weathermate Plus / #15 felt behind stone veneer	Adhered stone veneer /vinyl siding
3c	13 mm painted gypsum board	Latex paint (Class III)	2x4	R11 fiberglass batt	1” XPS	Weathermate Plus / #15 felt behind stone veneer	Adhered stone veneer /vinyl siding

TABLE 1: Walls for the Comparison of Exterior Insulation

Each wall has two exterior claddings. The bottom half is adhered stone veneer while the upper half is vinyl siding that is direct applied. A wetting apparatus was installed against the interior face of the sheathing at approximately 1/3 height. This was installed to allow intentional wetting simulating a water leak, such as might occur below an improperly flashed window penetration.

Experimental Variables and Hypothesis

The primary comparison for these walls addresses the effects of inward driven vapor. This comparison includes four analysis criteria:

1. The measured relative humidity at the mid-depth of the stud space,
2. The calculated relative humidity at the interior of the stud space based on measured data,
3. The measured moisture content of the framing, and
4. Photographic documentation and observations during the removal of the drywall.

It was hypothesized that Wall 3C with continuous exterior low permeance insulation and a Class III interior vapor control (latex paint on drywall) would have lower studspace relative humidity and framing moisture contents in the summer months than the more typical comparison test walls 3A and 3B.

OBSERVATIONS AND DISCUSSION

For context, a brief overview is provided below of inward vapor drives and how they may theoretically affect the test walls in this study. Results of experimental comparisons are then discussed.

Inward Vapor Drives

Solar induced inward vapor drives occur in building enclosures when an absorptive exterior cladding (such as masonry, adhered stone veneer, or some types of stucco) is used, wetted by rainfall, and heated by solar radiation. This combination of moisture and heat produces very high vapor pressures compared to the typical indoor vapor pressure and hence a vapor drive towards the interior is created. The amount of vapor diffusion is dependent on the vapor pressure gradient, that is, the difference in vapor pressures between two points in the assembly, and the vapor permeance of the building materials. The larger the vapor pressure gradient, the higher the potential vapor movement. A schematic of inward vapor drives is shown in Figure 4. Inward vapor drives can be minimized by using non-absorptive claddings, ensuring a ventilated cavity/capillary break behind the cladding, or using a lower vapor permeance layer between the absorptive cladding and structure.

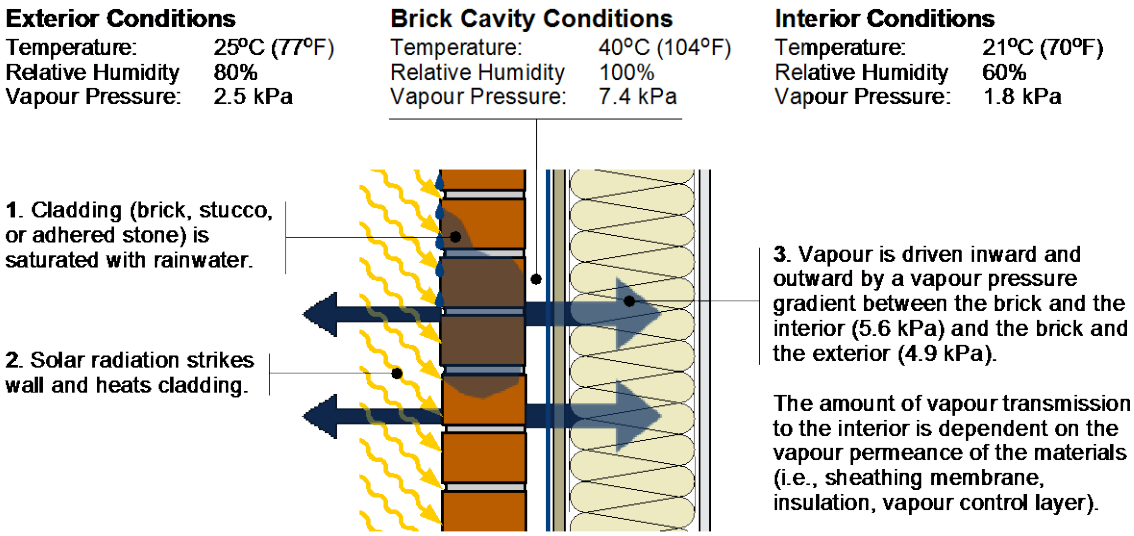

FIGURE 4: Inward Vapor Drive Schematic

Previous field testing has confirmed that inward vapor drives can be a durability issue with adhered stone veneers. In these previous tests, moisture accumulation was measured at the interior surface of the stud and the interior edge of the bottom plate. Both of these locations were monitored in the current test as shown in Figure 5 and Figure 6. In Walls 3a and 3b, moisture that is driven in could condense on the interior Class I vapor control layer of polyethylene if there was sufficient vapor. If sufficient condensation occurred in this situation, water would drain to the bottom of the poly where it would accumulate in the bottom plate and cause an increase in measured moisture content.

Because these test walls have two different claddings on the top and bottom half of the wall with an interconnected stud cavity between them, it may be possible that moisture driven into the stud cavity in the bottom half of the wall as a result of the adhered stone veneer could dry back to the exterior at the top half with naturally ventilated vinyl siding. The outward movement of moisture resulting in drying would occur more slowly than wetting as the vapor pressure gradient driving diffusion would be smaller to the exterior from inside the stud cavity.

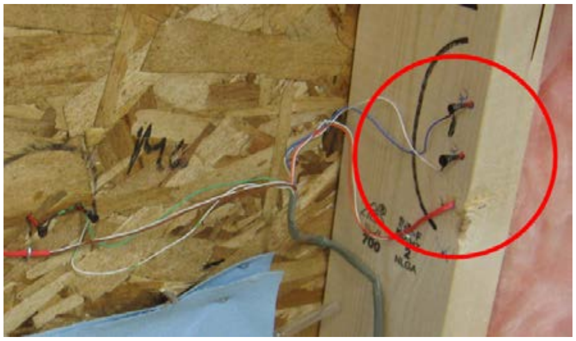

FIGURE 5: Moisture Content Sensor at Interior Edge of Stud

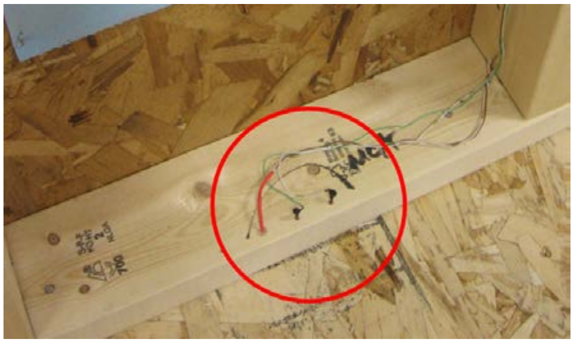

FIGURE 6: Moisture Content Sensor at Interior Edge of Bottom Plate

Relative Humidity Analysis

One indicator of inward vapor drive in the stud cavity is elevated relative humidity measurements in the stud cavity in the summer months. Two relative humidity sensors were installed in the stud cavity to measure the RH at 0.4 m (16 in.) and 2 m (80 in.) in height from the bottom plate at the mid depth between the drywall and the sheathing (halfway through the depth of the fiberglass batt insulation).

Figure 7 shows the measured cavity space RH at the lower measurement location for Walls 3A, 3B, and 3C on the South orientation. Every summer, the measured RH in Wall 3A and 3B increases significantly, exceeding 90% at the mid-depth of the stud space. The three other orientations all showed similar results with the highest measured RH in 3A and 3B on the West orientation, and the lowest measured RH in 3A and 3B on the North orientation, not including the Wall 3C on any orientation.

On all of the orientations, Wall 3C did not experience any elevated summertime RH levels indicative of inward vapor drive.

The vertical dashed red line on the relative humidity graph indicates the intentional wetting event when water was injected into the wetting apparatus. Analysis of the intentional wetting events is not included in the scope of this analysis and report.

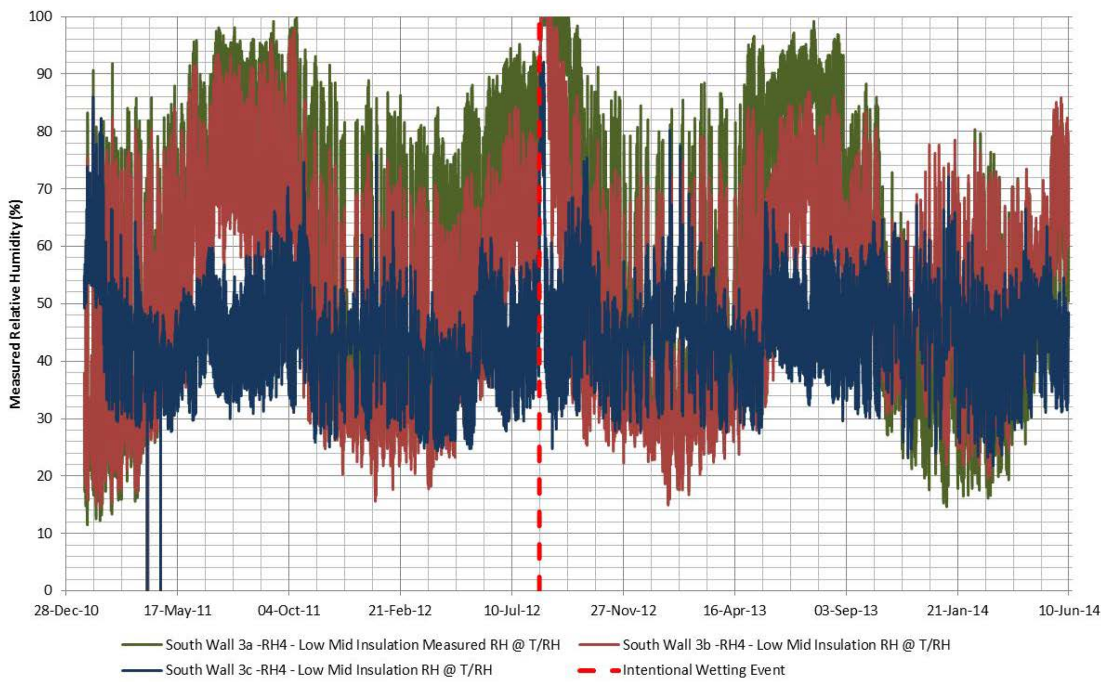

FIGURE 7: Measured Stud Space Relative Humidity in South Walls 3A, 3B and 3C

The relative humidity data shown in Figure 7 are based on sensors that were installed at the mid-depth point of the cavity so do not provide a measurement of the relative humidity at the drywall and actual possible inward driven condensation. The temperatures at the interior and exterior surfaces of the stud cavity are different than the temperature at mid-depth. In the summer months with elevated cladding temperatures, the temperature gradient decreases across the thermal insulation layer to the interior drywall surface. Therefore the temperature at the poly/drywall is lower, and the relative humidity is higher at the interior surface than the measured relative humidities shown in Figure 3.

The RH at the exterior surface of the drywall/poly was not measured. However, it can be calculated, because the temperature at that surface was measured. First we calculate the saturation vapor pressure at the mid-depth of the stud bay using the measured temperature for every hour.

$$P_{ws} = 1000 \cdot e^{\left(52.58 - \frac{6790.5}{T} - 5.028 \ln T\right)} \quad (1)$$

where

T is in degrees Kelvin

P_{ws} is in Pascals

The saturated vapor pressure calculated in Equation 1 applies if the air in the stud bay is completely saturated or 100% RH. It must be multiplied by the measured relative humidity (the ratio of vapor pressure to saturated vapor pressure) to calculate the vapor pressure at the mid-depth of the cavity, as shown in Equation 2.

$$P = P_{ws} \times RH \text{ [Pa]} \quad (2)$$

Because there is virtually no vapor pressure drop across fiberglass batt insulation (it has negligible vapor resistance), we can calculate the relative humidity at the drywall by using the ratio of the calculated vapor pressure in the cavity to the calculated saturated vapor pressure at the drywall using the measured drywall temperature and Equation 1. If the calculated vapor pressure at the mid-depth of the cavity is greater than the saturated vapor pressure at the drywall, the RH is 100% and condensation is occurring at the surface. If the vapor pressure at the mid-depth of the cavity is less than the saturation vapor pressure at the drywall, then the relative humidity at the drywall is the ratio of the calculated mid-depth vapor pressure and saturation vapor pressure at the drywall.

$$RH = {P_{calculated\ at\ mid-depth}}\Big/{P_{ws\ (calculated\ with\ measured\ drywall\ temp)}} \text{ [\%]} \quad (3)$$

Figure 8 shows a comparison on the South orientation of the measured RH at the mid-depth of the cavity (red line) and the calculated RH at the exterior surface of the drywall (green line). This analysis shows that on the South orientation, there are many hours of calculated condensation at the exterior surface of the drywall/poly often without periods of lower RH in between. It can be assumed that the relative humidity will increase at the drywall/poly in each comparison wall. In the winter months, when the drywall is the warmer side of the enclosure, the calculated relative humidity at the drywall is lower than the relative humidity at the mid-depth as expected.

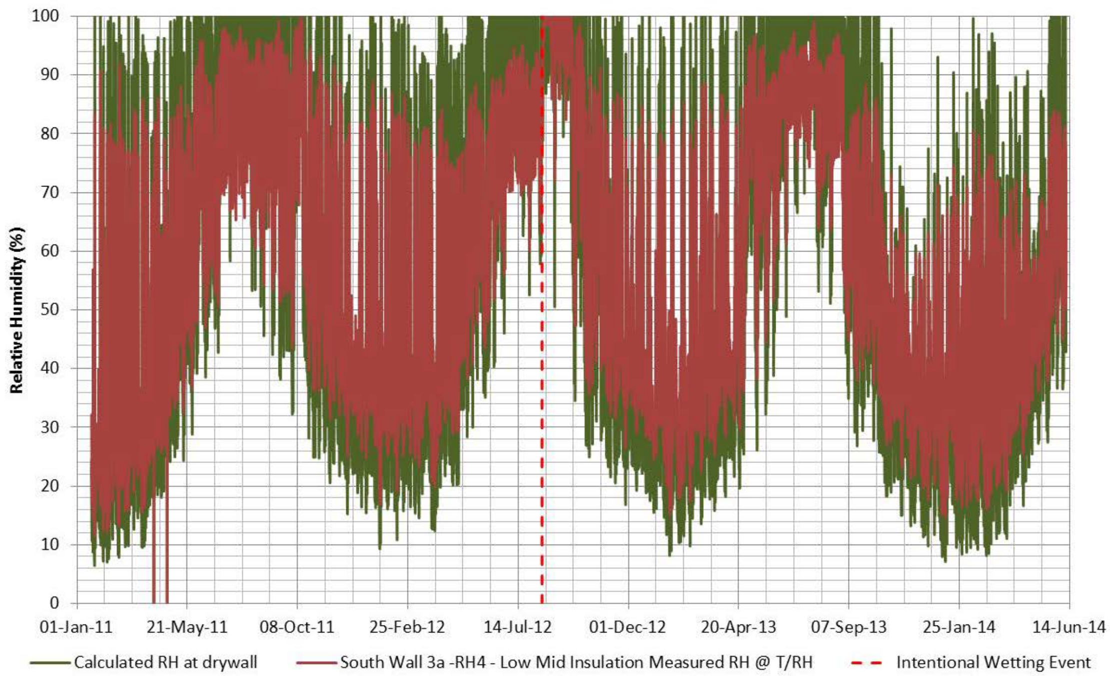

FIGURE 8: Calculated RH at the Exterior Surface of the Drywall Based on Measured RH at Mid-Depth of Stud Cavity

Moisture Content Analysis

Wood moisture content was measured at the interior edge of the bottom plate and vertical stud specifically to determine the effects of inward vapor drives that have condensed and caused liquid water run-down to the bottom plate. Figure 9 shows the two measured moisture contents for all three comparison walls on the East orientation.

The vertical dashed red line on the moisture content graphs indicates the intentional wetting event when water was injected into the wetting apparatus. Although analysis of the intentional wetting events is not included in the scope of this analysis report, it should be noted that any increase in moisture contents immediately following the dashed line are not indicative of inward vapor drives alone.

Measured increases in the moisture content of the bottom plate are typically a result of water condensing and accumulating. In other words, these increases indicate that water saturated the surface of the fiberglass batt and drained to the bottom of the wall, where it was absorbed into the bottom plate at a high enough volume to affect the moisture content of the wood bottom plate. Changes in the moisture content of the vertical stud are a result of water being absorbed into the wood framing.

On the East orientation there are elevated moisture contents in both Wall 3A and 3B in the first and third summers without an intentional wetting event. The increasing moisture contents match quite closely and it is difficult to see the moisture content lines for Wall 3A (blue lines) behind the Wall 3B lines (green). There are no increases in the bottom plate or stud moisture content in

Wall 3C with continuous exterior XPS insulation. All of the orientations have similar patterns to the East orientation. The greatest moisture content increases are on the West orientation, correlating to the highest measured relative humidity levels. On the North orientation, there was only a small increase in moisture content correlating to inward vapor drives as expected from the measured relative humidity data, but still sufficient condensation to drain to the bottom plate and increase the moisture content slightly. The vapor drives on the North side are generally not affected by solar radiation and the associated heating.

There was no increase in the bottom plate, or vertical framing moisture content measurement on Wall 3C, with continuous XPS exterior insulation and Class III vapor control, on any orientation.

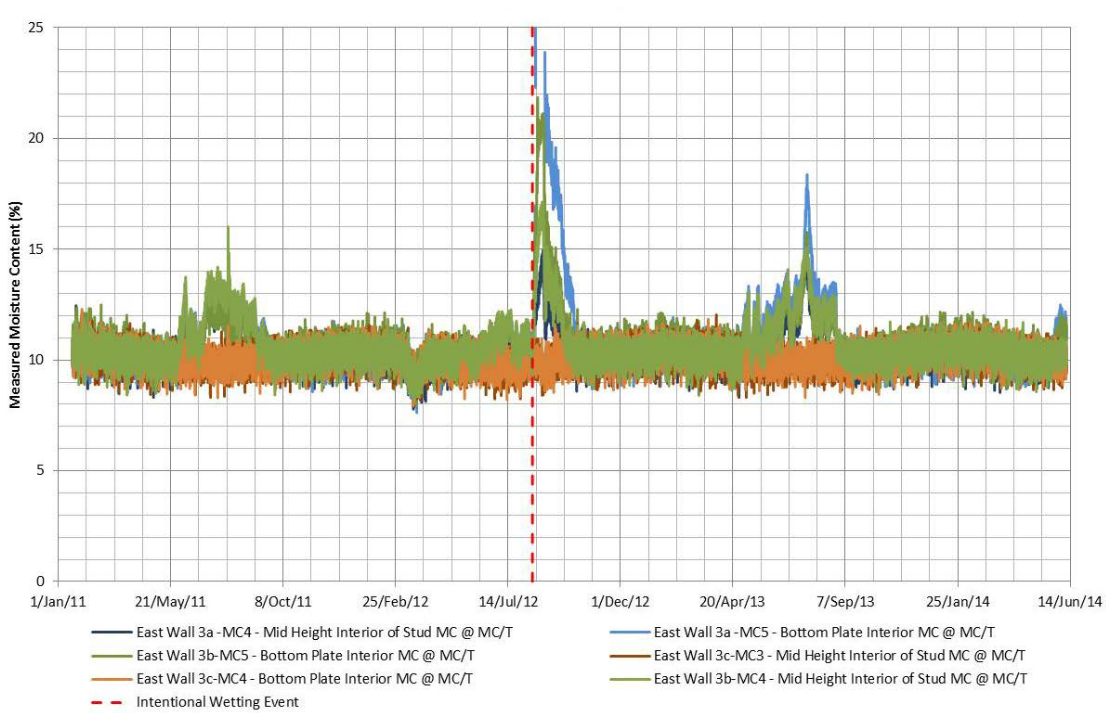

FIGURE 9: Measured Wood Moisture Contents in East Walls 3A, 3B and 3C

Investigation Photos

In August of 2013, the three comparison walls were opened on all four orientations to visually inspect the interior of the walls. Testing began in January of 2011, so the walls were opened during their third summer. All of the moisture related damage (i.e. staining, mold) was a result of only two and a half years of exposure. Most of the walls with poly (3A and 3B on all four orientations) had condensation present during the inspection. Nearly all of the 3A and 3B walls had some degree of staining on the bottom plate as a result of moisture accumulation from run down. The West walls had the greatest staining of all four orientations. North 3A and North 3B were the most pristine of all the poly walls as a result of having the least solar exposure and minimal inward solar drives. Wall 3C with continuous exterior insulation and latex paint vapor control on all orientations showed no evidence of moisture accumulation or staining. The following three photos show examples of the condensation and staining observed during the August 2013 investigation.

FIGURE 10: West Wall 3A Bottom Plate.
Note: Staining is visible on the interior surface of the bottom plate where water has drained down the poly and become trapped at the bottom between the taped edge of the poly and the wood. This was the worst observed staining of all poly walls. Some staining is also evident on the side of the vertical stud at the interior edge.

FIGURE 11: West Wall 3B Poly.
Note: There was sufficient condensation on the poly to accumulate into large, easily visible drops. When there is sufficient accumulation, it will drain to the bottom plate, and wet the insulation in the cavity. In some of the poly walls, there was only a little condensation, which had not yet formed large droplets.

FIGURE 12: West Wall 3C Bottom Plate and XPS.
Note: There is no staining on the top or inside edge of the bottom plate, or on the surface of the XPS. There is no corrosion of the fastener in the bottom plate.

CONCLUSIONS

Typically, inward vapor drives and related moisture accumulation are associated with the southern hotter climates. However, this study shows that even in Midland Michigan, located in IECC climate zone 5, vapor can be driven into the enclosure with a typically constructed moisture storage cladding such as adhered stone veneer. There were elevated summertime stud space RH measurements in Walls 3A and 3B on all four orientations. The West orientation had the highest measured RH in the stud space, and the North orientation had the lowest measured RH in the stud space, although there was still evidence of summertime inward drives.

The inward vapor drive in climate zone 5 is influenced by an interior vapor control layer to reduce the risk of outward movement of vapor/air in the winter (which could result in cold weather moisture accumulation in the sheathing). Typically the interior vapor control is poly, although Kraft paper is allowed by code as a vapor control layer. Latex paint is allowed when R-5 exterior insulating sheathing is used. Results show that poly can be problematic by trapping the moisture in the studspace, resulting in elevated relative humidities and condensation on the poly in the summer months. There were elevated summertime moisture content measurements at the interior surface of the bottom plate and vertical framing in Wall 3A and Wall 3B on every orientation indicating the presence of high moisture loads and condensation on the poly. The West orientation generally had the highest measured bottom plate moisture contents and the North orientation had the lowest measured moisture content increases, although there was still evidence of increases on the North orientation. Wall 3C on all four orientations with continuous XPS insulation and a Class III interior vapor control layer had no elevated moisture contents as a result of summertime inward vapor drives.

In a wall assembly with continuous exterior insulation, the requirement for interior vapor control is reduced, because there is less risk of wintertime cold weather moisture accumulation. The combination of a low permeance continuous exterior insulation in combination with a higher vapor permeance interior layer results in significantly reduced moisture in the cavity as a result of summertime inward vapor drives, and no indications of moisture related durability issues during a visual inspection of the wall framing and cavities. Wall 3C on all four orientations with continuous XPS insulation and a Class III interior vapor control layer had no elevated relative humidities as a result of summertime inward vapor drives.

ACKNOWLEDGEMENTS

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