Effect of Cladding Systems on Moisture Performance of Wood-Framed Walls in a Mixed-Humid Climate

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ABSTRACT

A 22-month field investigation of nine different north- and south-oriented wood-framed wall assemblies was conducted to determine the moisture performance of various wall construction types, most of which incorporated absorptive cladding. The study was conducted on the campus of the National Association of Home Builders (NAHB) Research Center, in Upper Marlboro, MD, 20 miles east of Washington, DC, in a mixed humid climate. Moisture content of the sheathing and wall cavity temperatures were measured at various points in each wall section. The primary performance measure was moisture content of the wood-based structural sheathing.

Under normal weather exposure, the studs and sheathing in all walls investigated remained well below 20% moisture content. South-facing walls with direct solar exposure resulted in dryer sheathing. Walls with non-absorptive cladding (vinyl siding and insulated vinyl siding) had among the lowest sheathing moisture contents recorded in the study; this was the case for walls that faced either north or south. Low sheathing moisture contents were also recorded in the south-facing walls with (a relatively dark color) manufactured stone cladding and in the south-facing wall with brick veneer cladding.

Controlled injections of water behind the cladding indicated that some walls were less able to drain (or otherwise dissipate) the injected water than were others. Stucco-clad walls with only one layer of water-resistive barrier (WRB) showed the least ability to dissipate injected water. Walls with manufactured stone cladding (which incorporated two layers of WRB) showed a lesser ability to dissipate injected water than walls with most of the other cladding systems, but greater ability than stucco-clad walls with a single layer of WRB.

INTRODUCTION

Moisture issues such as mold and rot, especially in exterior walls, have become a growing concern in residential construction, particularly as building envelopes have become tighter and have incorporated higher levels of thermal insulation as a result of more stringent energy codes and a growing consumer demand for comfortable and energy-efficient homes. Older homes, where wall insulation levels were lower or nonexistent and air infiltration, beyond minimizing drafts, was not a concern, are generally believed to be more forgiving of minor water intrusion because of their higher capability for natural drying. Therefore, the design of walls constructed to current specifications needs to include consideration of the ability to manage moisture, in addition to energy efficiency requirements. This study investigated moisture conditions in a variety of wall assemblies that meet current building code requirements.

Builders are often influenced by architects and home buyers to select exterior cladding systems based on aesthetic considerations. According to US Census Bureau (2009a) statistics, over half of all new homes are clad with absorptive materials such as brick, stucco, wood, fiber cement, and stone (Figure 1). Especially in humid climates, the increased popularity of absorptive claddings has led to a growing number of problems with moisture accumulation in exterior wall systems. The problems have been exacerbated by complicated

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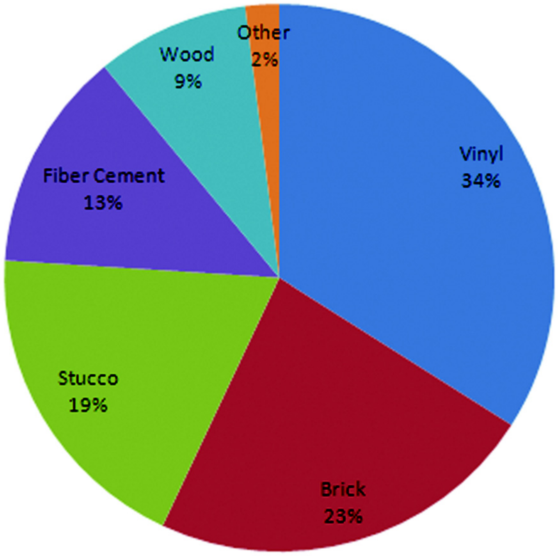

Figure 1 *Principal type of exterior wall cladding on new construction.*

Source: US Census (2009b).

architecture, fewer overhangs, and confusing water and vapor barrier requirements. Concern over the effect of moisture on the durability of homes provided the impetus to study the hygrothermal performance of walls with various exterior cladding systems.

Every climate has its own characteristics that must be considered when designing a wall system. The mixed humid climate has unique conditions, which typically include moisture migration from the inside of a structure during the winter and from the outside during the summer. These dynamic hygrothermic conditions can be problematic for certain wall assemblies. The mixed humid climate is defined by the following characteristics: (1) more than 20 in. of annual precipitation, (2) fewer than 5400 annual heating degree days (base 65°F), and (3) an average monthly winter temperature below 45°F.

WOOD MOISTURE THRESHOLDS

There are industry-established moisture thresholds for wood products at which durability or performance problems may occur. The threshold levels are driven by concerns relating to rated structural performance, decay, and mold. Wood building materials, and assemblies constructed of wood and wood-based products, perform best when they remain dry.

Prominent organizations in the wood industry have defined a dry condition for engineered wood products (EWP) as moisture content (MC) of less than 16%, and for solid wood less than 19%; these levels relate to rated structural performance. When wood products are used in conditions where moisture contents exceed these levels, the National Design Specification requires that wet service factors be applied (American Forest and Paper Association 2005). The service factors derate the design values for material strength and stiffness. Engineers apply these service factors when they expect that in-service moisture conditions will exceed the thresholds (16% for EWP; 19% for wood). The primary reason the threshold moisture content is set lower for engineered wood products than for solid wood is that engineered wood products have lower equilibrium moisture contents than solid wood at equivalent relative humidity conditions (Carll and Wiedenhoeft 2009).

The dry design threshold conditions are essentially equivalent to equilibrium moisture conditions with room temperature air and a relative humidity just below 90% (see Table 3-4 in Simpson and TenWolde [1999]). This corresponds with a moisture level just below the long-recognized 20% moisture content (MC) threshold for wood, which will prevent propagation of decay, even in wood previously infected with decay fungi (Carll and Highley 1999). In fresh, uninfected wood and wood products, decay is only likely to be established when moisture content exceeds the fiber saturation point (average 30% MC in lumber) at temperatures between 50°F and 95°F. The long-recognized 20% threshold provides a margin of safety with regard to preventing decay propagation.

The same moisture threshold value that determines application of wet service factors is also assumed by the wood products industry to be the upper limit of in-service moisture content limit for wood-based structural panels (APA 2002). The industry applies the same assumed limit to in-service moisture content of both plywood and oriented strand board (OSB) panels.

Conditions necessary to minimize mold growth have been outlined in the first edition of *ANSI/ASHRAE Standard 160-2009: Criteria for Moisture-Control Design Analysis in Buildings*. The values in the standard translate to lower maximum allowable in-service moisture contents for engineered wood products than the value assumed by the industry (APA 2002). The mold growth prevention criteria outlined in *ASHRAE Standard 160* consist of three parameters: time, temperature, and surface relative humidity. The criterion with the longest time duration element (30-day running average) specifies that surface relative humidity not exceed 80%; this corresponds with a solid wood moisture content of 16%, which approximately equates to a plywood MC of 14% and OSB MC of 13% (Richards et al. 1992).

STUDY OBJECTIVE

The objective of this research was to quantify the field performance of wood-frame walls clad with a variety of common claddings in a mixed-humid climate. Performance was judged primarily on measurements of in-situ moisture content of the wood-based (oriented strand board or plywood) sheathing. Nine different wall designs were evaluated in this study.

The study was designed to identify relative moisture performance for light frame wall assemblies in a mixed humid climate with a variety of cladding systems. Some of the wall assemblies differed substantially in both cladding type and moisture handling, while others were of similar type and appearance but differed with regard to their moisture drainage design. A related study objective was to identify the relative capabilities of the different wall assemblies to dissipate moisture should wetting occur.

TECHNICAL APPROACH

Selection of the wall designs evaluated in this study was based in part on their use in new construction. Wall cladding types selected in this study represent roughly 90% of the primary claddings used in new construction in the United States (see Figure 1). The various wall constructions were expected to exhibit a range of hygrothermal performance. Final selection of the walls was made by industry professionals on the basis of their common use and practical constructability.

For each of the nine wall designs, a pair of wall test panels was evaluated, one of which was placed in north-facing exposure, while the other was placed in south-facing exposure. Each wall panel pair was installed in one of two test structures constructed on the NAHB Research Center campus in Upper Marlboro, MD. Five of the wall pairs were commissioned in January 2008; these were installed in the first test structure. The other four wall pairs were commissioned in November 2008; these were installed in a second test structure, also located on the National Association of Home Builders (NAHB) Research Center campus. A solar site survey was conducted to verify that walls in the two structures received equal solar exposure. Moisture conditions in the nine pairs were monitored through October 2009. The interior of each building was climate controlled (temperature and winter humidity) to simulate common indoor residential conditions. Detailed measurements of indoor and outdoor environmental conditions and the moisture content of studs and sheathing were used to determine hygrothermal performance of each assembly.

The study was thus primarily based on field monitoring of moisture conditions in test wall panels, but also involved additional testing, some of which was conducted in the laboratory and some of which was conducted in the field.

FIELD MONITORING

Both test structures had a nominal footprint of 8 ft by 48 ft (Figure 2). Each building allowed for five pairs of 8 ft wide by 9 ft high wall test panels to be installed as exterior wall sections, with one panel of each pair having cardinally oriented southern exposure and the other panel of the pair having northern exposure. Test structure 1 was constructed on site and was commissioned in January 2008. The second building was prefabricated and delivered to the site; walls were then added on site, with data collection for the walls beginning in November 2008.

The 8 ft × 9 ft test panels were framed with 2 in. × 4 in. studs, sheathed with OSB or plywood. The panels included various combinations of cladding and drainage strategies, which are described in the following section of this report. A window is located on the west end of the building and an entrance door is located on the east. The interior was finished with two coats of latex paint over 1/2 in. drywall. The perimeter of each wall section was caulked to eliminate flanking air infiltration. The floor is raised approximately 2 ft from the ground and insulated with R-19 fiberglass batt insulation. The roof is shingled on 4/12 pitch trusses and insulated to R-30 at the attic ceiling interface. Even though the first structure is permanent and the second is semimobile, they were constructed to nearly identical specifications. Roof overhang was limited to the 4 in. gutter; test panel exteriors therefore had appreciable exposure to the elements. All products were installed in accordance with manufacturer recommendations or, if recommendations were unavailable, in accordance with the prevailing building code (IRC 2003).

Figure 2 *Test buildings 1 (right) and 2 (left).*

Portable air conditioners were set to limit the maximum interior summer temperature to 78°F, and resistance heat maintained indoor temperature in the winter at 70°F. A humidifier maintained a winter indoor relative humidity between 25 and 30%.

Wall Panel Assemblies

The nine wall panel designs evaluated in the study are outlined in Table 1. The panels included four with stucco cladding. Three of these had OSB sheathing, and these three differed with regard to drainage strategy for the cladding system; the fourth stucco-clad wall design had plywood sheathing. One of the wall designs had synthetic stone cladding, one had lap fiber-cement siding, and one had brick veneer cladding. The wall with brick veneer had a nominal 1 in. gap between the sheathing (covered with a water-resistive barrier) and the back face of the brick. Two wall designs had nonabsorptive cladding; one of these had insulated vinyl

Table 1. Test Wall Configurations

Panel #	Building	Sheathing	Water Resistive Barrier	Exterior Cladding
1- Vinyl	1	7/16 in. OSB	Spun bonded polyolefin	Vinyl siding
2- Stucco 1	1	7/16 in. OSB	1 layer No. 15 felt	Stucco
3- Stucco 2	1	7/16 in. OSB	2 layers No. 15 felt	Stucco
4- Stucco Vent	1	7/16 in. OSB	SBP 3/8” gap #15 felt	Stucco
5- Manu Stone	1	7/16 in. OSB	2 layers No. 15 felt	Manufactured stone
6- Ins Siding	2	7/16 in. OSB	Spun bonded polyolefin	Insulated Vinyl Siding
7- Fiber Cement	2	7/16 in. OSB	Spun bonded polyolefin	Fiber Cement Siding
8- Stucco/Plywood	2	1/2 in. Plywood	2 layers No. 15 felt	Stucco
9- Brick	2	7/16 in. OSB	Spun bonded polyolefin	Brick

siding, while the other had unbacked vinyl siding. As indicated previously, all walls were constructed with 2 × 4 framing; studs were at 16 in. (405 mm) on-center (o.c.) spacing. Stud cavities were insulated with R-13 kraft-faced glass fiber batt insulation, which was face-stapled.

Sensor Placement and Data Collection

In order to monitor conditions within wall sections, each was instrumented with 44 sensors (Figure 3) capable of recording temperatures, relative humidity, and wood moisture content. Each sensor included two, uninsulated 2 in. stainless steel screws that secure it to wood framing or sheathing. The screws penetrated 0.4 in. (10 mm) into the substrate to obtain a conductance reading related to substrate moisture content. The sensors had an MC measurement range of 7% to 40% (initially calibrated to Douglas fir), a temperature range of –40°F (–40°C) to 185°F (85°C), and a relative humidity range from 0% to 100%. The measurement interval was programmable, and was set to 30 minutes. Data were transmitted wirelessly at each reading time to a local gateway, which in turn periodically transmitted the data via the Internet to a database maintained by the sensor manufacturer. The sensor manufacturer provided temperature compensation of the conductance readings obtained from the screw electrodes. The temperature reading that was used for compensation was, however, taken at a location separated from the screw tips by roughly 35 mm. For conductance readings taken in sheathing, the temperature compensation may, under some conditions, thus be less than ideal. All moisture content readings were gravimetrically calibrated to the material (plywood and OSB, inclusive of resin mass). The calibration adjustment that was found necessary for plywood was substantial (considerably larger than that needed for either SPF lumber or OSB), particularly at higher moisture content levels. The nature of the calibration adjustment that was found necessary for plywood concurred with that found necessary by Glass and Carll (2009).

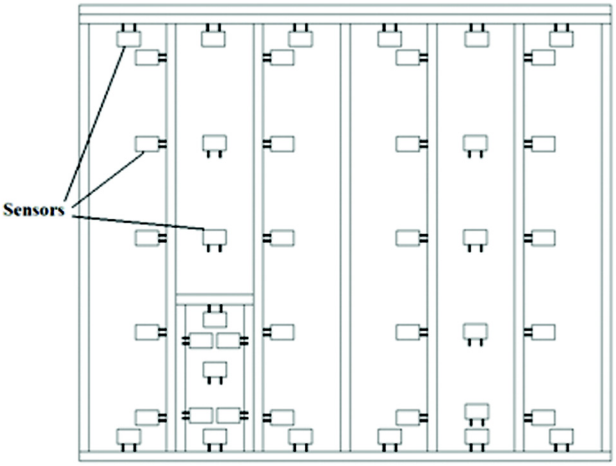

Figure 3 *Sensor locations and wall framing.*

Weather Data

A weather station was mounted on the roof of the first test structure. The station included a wind vane and anemometer to measure wind direction and speed, a temperature and humidity sensor, a tipping-bucket rain gage, and a horizontally installed spectral pyranometer to measure solar radiation. A custom-designed, wind-driven rain gauge and a vertically positioned spectral pyranometer were also installed on the north and south walls of the first test structure to better understand the conditions at the wall surface.

Weather conditions over the 2008–2009 monitoring period were reasonably similar to the 30-year historical average conditions at Andrews Air Force Base, located roughly 10 miles from the NAHBRC campus (Table 2). For the last 12 months of the monitoring period (November 2008–October 2009), the number of heating degree days was nearly identical to the historical average (4440 vs. 4421 HDD). The summer of 2009 was milder than average, with only 1097 CDD compared to a 1241 average. Rainfall was also close to

Table 2. Weather Data and Historical Averages

Andrews AFB - ASHRAE/NOAA Historical Averages					NAHBRC Weather Station Data				
	Average Temp., °F	Precipitation, in.	Heating Degree Days, °F	Cooling Degree Days, °F		Average Temp., °F	Precipitation, in.	Heating Degree Days, °F	Cooling Degree Days, °F
January	34.6	3.5	943	0	Jan. 08	36.5	1.1	798	0
February	37.7	3.0	764	0	Feb. 08	39.1	2.9	754	2
March	45.1	3.9	622	5	Mar. 08	46.0	2.8	476	0
April	54.8	3.0	324	19	Apr. 08	56.4	7.1	264	14
May	63.8	3.9	117	79	May 08	62.7	3.4	126	54
June	72.7	3.4	12	242	Jun. 08	75.2	5.6	0	305
July	77.7	3.9	1	394	Jul. 08	77.1	3.5	0	375
August	75.6	3.7	2	330	Aug. 08	73.0	2.3	0	249
September	68.4	4.0	44	145	Sep. 08	69.3	4.5	25	154
October	57.3	3.2	263	24	Oct. 08	55.5	1.2	311	17
November	48.1	3.1	510	3	Nov. 08	46.1	2.7	566	0
December	38.6	3.4	819	0	Dec. 08	40.4	2.5	762	0
Year	**56.3**	**42.0**	**4421**	**1241**	**Year**	**56.4**	**39.6**	**4081**	**1170**
January	34.6	3.5	943	0	Jan. 09	30.7	2.6	1062	0
February	37.7	3.0	764	0	Feb. 09	39.8	0.3	706	0
March	45.1	3.9	622	5	Mar. 09	44.6	1.5	638	4
April	54.8	3.0	324	19	Apr. 09	56.6	4.0	305	51
May	63.8	3.9	117	79	May 09	64.1	3.9	83	61
June	72.7	3.4	12	242	Jun. 09	72.2	7.9	10	226
July	77.7	3.9	1	394	Jul. 09	74.9	1.0	0	306
August	75.6	3.7	2	330	Aug. 09	76.5	4.6	0	357
September	68.4	4.0	44	145	Sep. 09	66.6	2.8	31	80
October	57.3	3.2	263	24	Oct. 09	56.5	6.0	277	14
Jan–Oct	**58.8**	**35.5**	**3092**	**1238**	**Jan–Oct**	**58.2**	**34.6**	**3112**	**1097**

historical average with the 12-month accumulation totaling 39.8 in.; just 2.1 in. shy of normal.

ADDITIONAL TESTING

Permeance Testing

Published data for vapor permeance were available for some of the materials used in the wall sections. Laboratory testing of the materials used in construction of test wall sections was nonetheless performed. This was deemed appropriate to account for product variation, which may occur between manufacturers, manufacturing plants, and production runs within a given manufacturing plant. Testing was according to *ASTM E96-05, Standard Test Methods for Water Vapor Transmission of Materials*. Permeance tests were performed on the same lots of material that were used to construct wall panels. Test results are presented in Table 3. The test values for most materials were in general concurrence with published values (Kumaran et al. 2002; ASHRAE 2009). The measured values for permeance of painted gypsum drywall were, however, substantially higher than the values listed by ASHRAE for paint films, or by Kumaran et al. for painted gypsum drywall.

Vented Cladding Air Change Rate Testing

As indicated in Table 1, one of the stucco-clad wall designs selected for evaluation (wall pair #4) included a 3/8 in. (10 mm) gap between the cladding and the sheathing. The top of the furred space was blocked, but the bottom was open to allow drainage and some degree of ventilation. In order to characterize the ventilation rate of the space over the 22-month monitoring period, tracer gas testing was conducted on six

Table 3. Tested Wall Material Specifications

Material	Thickness, in.	Density, lb/ft^3	Permeance (Dry Cup)	Permeance (Wet Cup)
Drywall	0.489	37.9	48	44
Painted drywall	0.496	38.6	40	40
OSB	0.448	41.5	4.1	4.5
Stucco	0.758	51.2	4.3	5.5
Manufactured stone (trimmed)	0.767	99.9	2.8	5.1
Spun bonded polyolefin	0.005	35.4	36	35
No. 15 asphalt felt	0.018	68.3	6.9	13.9
Stud (trimmed)	0.699	21.5	0.6	6.1

separate days during the test period to determine air exchange rate in the space between the sheathing and the stucco cladding of wall pair #4. Tests were performed by injecting sulfur hexafluoride (SF_6) into the cavity, then monitoring the decay of the SF_6 concentration with a gas analyzer using the *ASTM Standard E741-00* protocol.

Although there were insufficient test data to adequately correlate vented cladding air exchange rates with environmental conditions, the data nonetheless indicated an approximate air exchange rate and provided some indication of meteorological influences on the exchange rate. Measured air exchange rates varied between 2 and 28 air changes per hour, and generally were higher in the south wall, in the winter, and during the day.

WATER INJECTION TESTING

Water resistive barriers (WRBs) are intended to block passage of water that breaches the cladding system. Penetration of water behind a WRB is, however, not unusual, and often occurs around windows and other penetrations. In order to understand how the wall sections responded when water breached their cladding systems, controlled water injections were made into each of the wall sections. The water injections were performed daily over five consecutive days in August 2009. An increase in sheathing moisture readings relative to those in an unaffected area indicated the degree to which the injected water was absorbed into the sheathing. The readings from one of the seven sensors in the sheathing in each of the test wall sections were potentially affected by the water injection events.

The five consecutive days during which injections were made began at noon on August 3, 2009. On each day, 30 mL of water was injected through each of two 1/4 in. hoses, installed at the time of construction, which directed water to each side of the WRB (for a daily injection of 60 mL total). One of the tubes terminated between the WRB and the cladding (or between the WRBs when two WRB layers were present), while the other terminated between the WRB and the sheathing. The successive injections were intended to simulate a leak from a multiday storm.

Moisture Content of Sheathing

Over the course of the testing, sheathing moisture content was consistently well below 18%. Only the first weekly reading for the wall pair with plywood sheathing (which was stucco-clad) was in excess of 20%. During the first week of monitoring, construction moisture in walls with wet-placed cladding systems was being dissipated. Once the moisture from wet-placed cladding systems was dissipated, the overwhelming majority of sheathing measurements remained at or below 16% MC. The exceptions were brief excursions above 16% sheathing MC in both plywood-sheathed walls and the north-facing stucco wall with one WRB layer. During these excursions, the moisture content levels nonetheless remained below the respective equilibrium values at 90% relative humidity (Richards et al. 1992; Kumaran et al. 2002).

Walls with “wet-placed” claddings, such as stucco and manufactured stone, generally had higher sheathing moisture contents than walls with other claddings. Sheathing moisture contents in south-facing walls with unventilated wet-placed claddings were generally higher than in south-facing walls with other cladding systems; the exception to this was the wall with manufactured stone cladding, which showed relatively dry readings in the sheathing. This, as explained later, appears to have been associated with warm sheathing temperature conditions in that wall, attributed to direct solar gains.

The wall pair that consistently had among the highest sheathing moisture content was the pair with plywood sheathing (which had stucco cladding over two layers of felt). Figures 4 and 5 show that the plywood had elevated moisture content at the start of monitoring. This suggests significant wetting of the plywood during installation of the (wet-placed) cladding system. This may reflect an inherent difference between plywood and OSB: in an unweathered condition, OSB is more resistant to water absorption than is sheathing-grade plywood (Quarles and Flynn 2001; Kumaran et al 2002). The stucco on the wall pair with plywood sheathing was, however, applied at a slightly different time of year than any of the four other wet-placed claddings (which were all on the other test building) and was applied by a different contractor. This difference in construction history could have been a contributing factor that affected wetting of the sheathing. In

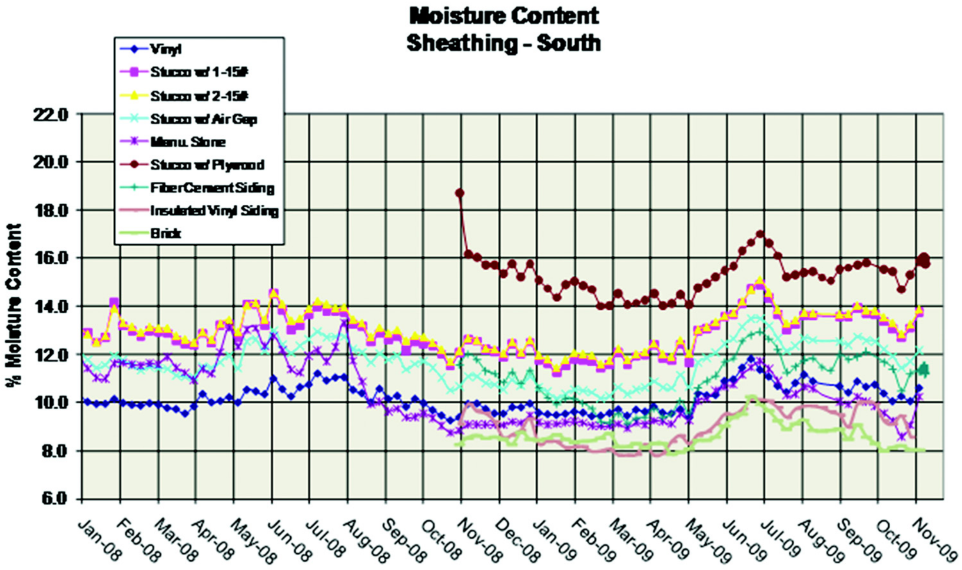

Figure 4 *Sheathing moisture content: south.*

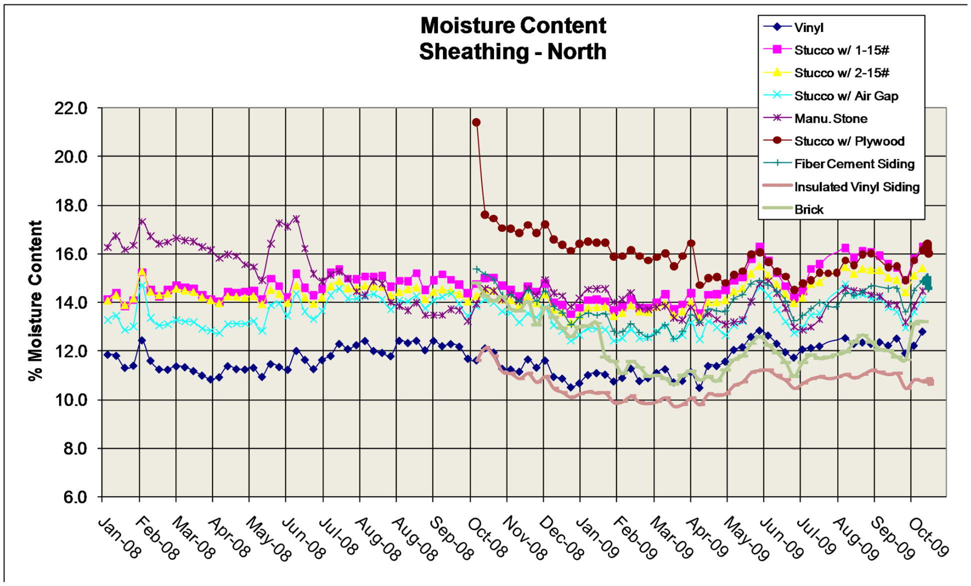

Figure 5 *Sheathing moisture content: north.*

the north-facing exposure, sheathing moisture content in the plywood-sheathed wall reached levels essentially comparable to those in an otherwise similar OSB-sheathed wall after roughly 7 months (Figure 5). In south-facing exposure, in contrast, sheathing moisture content the plywood-sheathed wall remained higher than in any other wall over the length of the monitoring period (Figure 4).

The north-facing wall with manufactured stone cladding showed elevated sheathing MC levels at commissioning, although not as high as in the stucco-clad wall with plywood sheathing. Sheathing moisture contents in this wall settled to a level below 15% after approximately 6 months. This wall took longer to dissipate its construction moisture than any other wall, except for the wall with plywood sheathing. After dissipation of the construction moisture, sheathing MC levels in this wall were roughly equivalent to those in unvented north-facing stucco-clad walls. Sheathing moisture contents of walls clad with manufactured stone were highly dependent on the direction the walls faced. From September 2008 onward, the south-facing wall with stone cladding showed

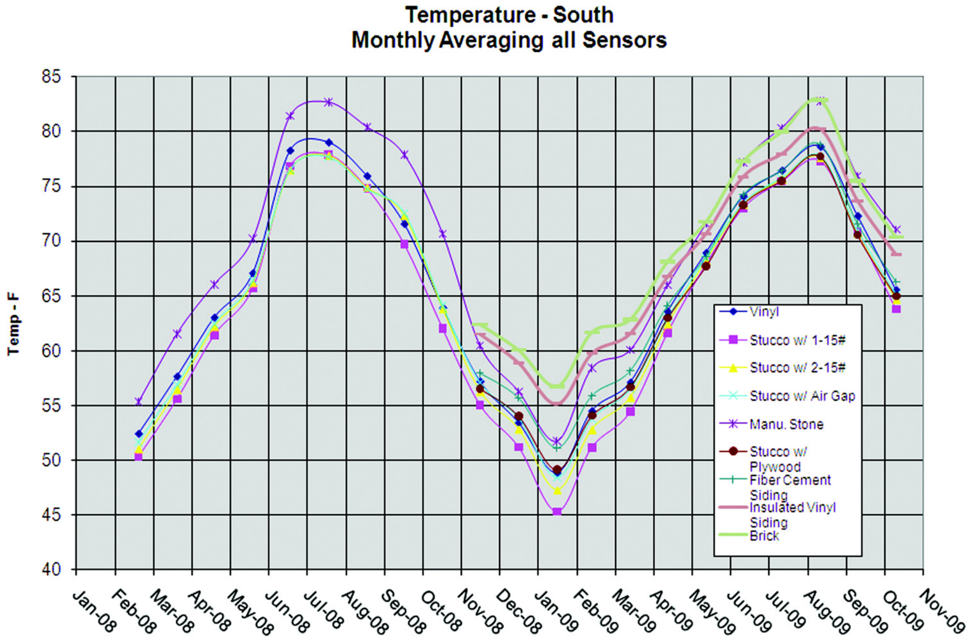

Figure 6 *Wall cavity temperature: south.*

lower sheathing moisture content than most other walls, whereas the corresponding north-facing wall showed higher sheathing moisture contents than most other walls, and in January and February 2009 showed higher sheathing moisture content than any other wall.

In summary, 3 of the 18 walls monitored in this study showed sheathing moisture contents (after dissipation of construction moisture) that sometimes exceeded 16%. These were the stucco-clad walls sheathed with plywood (north- and south-facing exposures) and the north-facing stucco-clad wall with OSB sheathing and a single layer of #15 felt. When in-service sheathing moisture contents exceeded 16%, they did so for limited periods of time. The three best performing walls were insulated vinyl siding, brick with a 1 in. air gap, and traditional vinyl siding.

Wall Cavity Temperature

Over the monitoring period, wall cavity temperatures in south-facing walls were consistently warmer than in north-facing walls (Figure 6). During winter months, the warmest wall in north-facing orientation was the wall clad with insulated vinyl siding; the next warmest cavity temperatures during winter (after those in the wall clad with insulated siding) were observed in the wall clad with brick veneer, followed by the wall clad with lap fiber cement siding (Figure 7). This indicates that air spaces behind the cladding system (including the discontinuous spaces provided by installation of lap siding) provided some thermal benefit during winter.

Figure 6 clearly indicates that the south-facing walls with brick and manufactured stone cladding had notably higher within-wall temperatures than were found in most of the other walls over most of the monitoring period. Over the period of November 2008 through early April 2009, the wall with insulated siding was warmer than the wall with manufactured stone cladding, but otherwise, the walls with brick and with manufactured stone claddings were the warmest walls over the monitoring period. The likely explanation for the relatively high temperatures in these walls is the ability of the cladding systems to absorb and store radiant solar gains. In the north-facing wall with manufactured stone cladding, within-wall temperatures did not differ substantially from those in walls clad with either stucco or uninsulated vinyl siding (Figure 7). The relatively high temperatures in south-facing walls with darker brick and stone cladding influenced moisture conditions in these walls.

Water Injection Testing

Water injection testing resulted in distinctly different moisture responses in different wall types. Only three of the nine wall pairs showed a sustained increase of greater than 0.5% moisture content. The wall pair that showed the greatest increase (3% north, 1.5% south) in sheathing moisture content had stucco cladding over a single layer of felt (Figures 8 and 9) for both orientations. The other two walls that showed a noticeable increase were the manufactured stone wall and the plywood sheathed stucco wall.

The wall pair with manufactured stone cladding showed an increase in sheathing moisture content in response to water injection testing, but to a lesser degree than the wall pair with stucco cladding and a single layer of WRB (Figures 8 and 9).

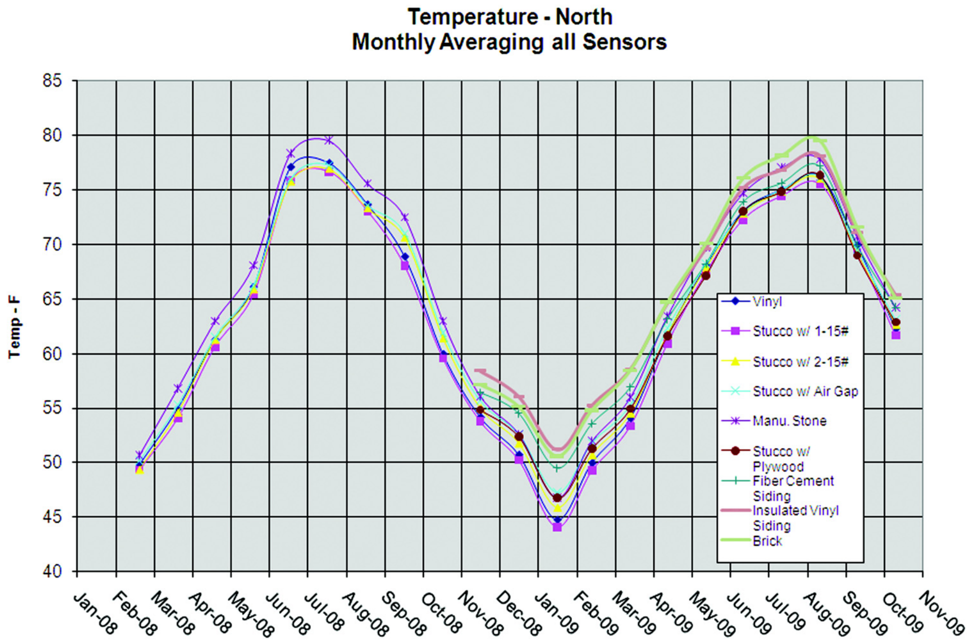

Figure 7 *Wall cavity temperature: north.*

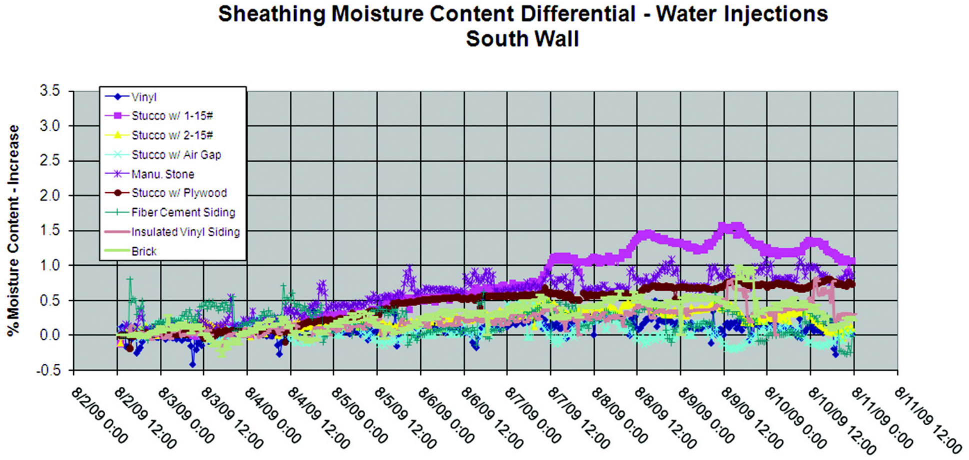

Figure 8 *Sheathing moisture content increase with water injections: south. Note: stucco wall with plywood readings were determined to be unreliable, and thus were not reported on this graph.*

As was the case for walls with stucco cladding and a single layer of felt, the increase in sheathing moisture content was greater in the north-facing wall of the pair than in the south-facing wall of the pair. The role of solar gain in dissipation of injected water thus appears significant.

The response of the stucco-clad walls with plywood sheathing was similar to that of the walls with manufactured stone cladding (Figures 8 and 9). The responses of these walls to water injection testing were greater than those of otherwise similar walls with OSB sheathing. This behavior concurs with the relative sheathing moisture content levels in plywood-sheathed versus OSB-sheathed walls in the same orientation and with the same cladding system (stucco over two layers of felt). As indicated previously, the differences may be associated with inherent differences between the sheathing materials. By the time that water injection tests were conducted, differences in construction history may be assumed to no longer have substantial influence; this would suggest that the differences were indeed largely due to differences between the sheathing materials. It should be noted, however, that the water injection tests, although they simulated a multiday storm, were nonetheless of limited duration, and thus may not

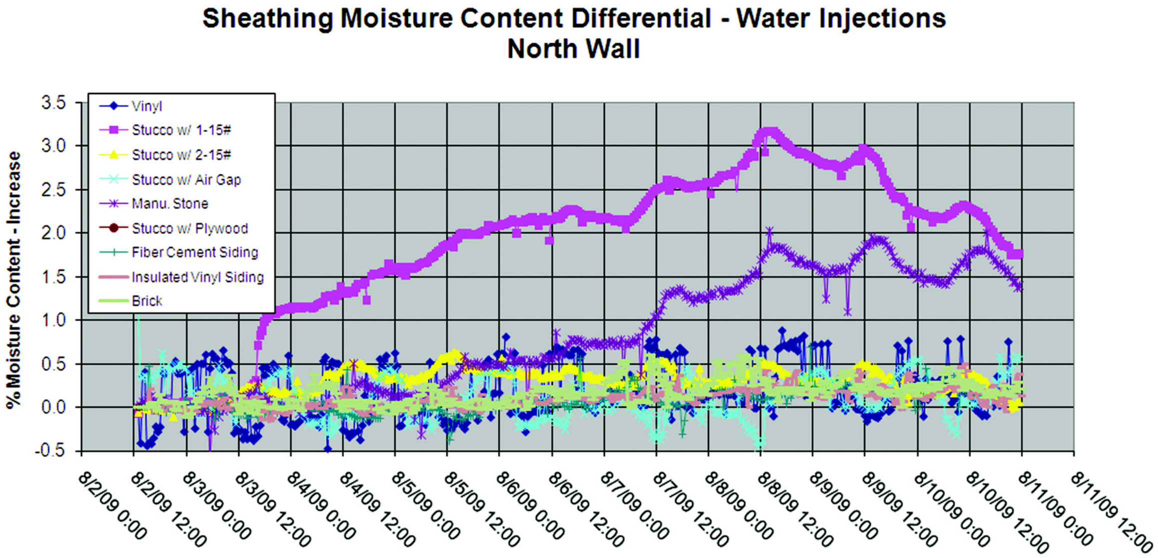

Figure 9 *Sheathing moisture content increase with water injections: north. Note: stucco wall with plywood readings were determined to be unreliable, and thus were not reported on this graph.*

necessarily be indicative of relative performance in walls that experience chronic leakage over weeks, months, or years.

CONCLUSIONS

Over the monitoring period, sheathing in all of the nine pairs of walls (18 walls) evaluated in this study generally remained below the industry-recognized moisture content threshold level of 16%, although there were some exceptions. Three of the wall pairs (six walls) did not incorporate wet-placed cladding materials; in these walls, and in walls with brick veneer cladding, there was little indication of construction moisture, and the sheathing in these walls remained substantially below 16% MC throughout the monitoring period. North-facing walls clad with manufactured stone and stucco-clad walls with plywood sheathing (facing either north or south) had the highest initial moisture contents and were the slowest to dry. In stucco-clad walls with plywood sheathing and in the north-facing stucco-clad wall with a single layer of #15 felt, there were periods after dissipation of construction moisture when sheathing moisture contents briefly exceeded 16%.

There were two primary mechanisms that acted to lower in-service moisture content of the wood-based sheathings: air circulation and wall temperature. Air circulation behind the cladding contributed to the drying capability of the vinyl siding, brick, stucco (3/8 in. furred), and, to a lesser extent, fiber cement siding. Higher wall cavity temperatures generally correlated with lower sheathing moisture contents. This was especially true with insulated vinyl siding and darker claddings with southern solar exposure such as brick and manufactured stone.

The 30-day mold-growth-minimizing criterion outlined in *ASHRAE Standard 160* (a running average surface RH below 80% RH) effectively specifies lower sheathing moisture contents than the 16% wet service factor threshold value. As indicated previously, an 80% surface RH value corresponds with approximately 13% MC for OSB and 14% MC for plywood. The *ASHRAE Standard 160* criterion also has a temperature component: the surface RH criterion applies when the 30-day running average temperature exceeds 41°F (5°C). The *ASHRAE Standard 160* criterion was not exceeded in six of the nine south-facing walls. The three south-facing walls in which the criterion was exceeded were stucco-clad and without an air gap. In contrast, the criterion was exceeded in six of the nine north-facing walls. The north-facing walls where the criterion was not exceeded were the walls clad with vinyl siding, insulated vinyl siding, and brick veneer. It is important to note that the mold-growth-inhibition criteria outlined in *ASHRAE Standard 160* are termed "conditions necessary to minimize mold growth." If the *ASHRAE Standard 160* criteria are exceeded, there is some risk of mold growth, but mold growth will not necessarily occur. *ASHRAE Standard 160* acknowledges that criteria for inhibition of mold are typically more restrictive than other moisture limitation criteria applicable to buildings; thus, this criterion was not considered determinate on the performance of the wall assemblies. In addition, core samples of the sheathing were examined at the conclusion of the study period, and no evidence of mold growth was observed on either side of the sheathing.

Additional observations, based on sheathing moisture content readings, were as follows:

- Orientation and solar exposure are important factors in wall performance. All north-facing walls experienced higher moisture and cavity humidity readings than the corresponding south-facing wall of the same construction.

- The wall pair with vented stucco cladding performed better than any other wall clad with stucco. The performance of this pair was similar to that of the wall pair with the fiber cement lap siding.
- The two walls with dark claddings performed quite differently on the south than the north. South-facing walls with brick (dark red) and manufactured stone (dark earth tones) had relatively high cavity temperatures throughout the monitoring period (although during cold weather, cavity temperatures in the wall with insulated siding were higher than in the wall with manufactured stone).
- The wall pair with insulated vinyl siding had the lowest all-around sheathing moisture content values. This is attributed to warmer within-wall temperatures during the heating season, which are afforded by the exterior insulation provided by the foam backing. The warmer temperatures result in lower within-wall relative humidity values, corresponding lower equilibrium moisture content, and increased drying capacity.
- The wall pair clad with brick veneer was among the driest of all the walls evaluated in this study. The 1 in. air gap along with the increased absorptance (darker color) evidently provided increased drying capability.
- Manufactured stone had the greatest sensitivity to orientation. Sheathing moisture content was reduced by nearly a third in the south-facing wall with manufactured stone cladding (14% north, 10% south). This was attributed to the higher wall cavity temperatures due to the radiant gains on the southern exposure.
- Vinyl siding generally provided for consistently dry sheathing conditions. The loose fit of the siding allowed the wall to dry from the inside toward the outside, while the siding also shed bulk moisture.
- A second layer of water-resistive barrier becomes critical for stucco applications when bulk moisture gets behind the cladding. Stucco-clad walls with one and two WRB layers performed comparably under normal exposure; however, when moisture was injected, the sheathing in the wall with two layers of WRB had virtually no increase in moisture content, while the sheathing in both the north- and south-facing stucco-clad walls with a single layer of WRB saw moisture increases of up to 3.5% MC over the five-day injection period.
- The north-facing wall with manufactured stone cladding, which had two WRB layers, did not perform as well as the north-facing stucco-clad wall with two WRB layers and the same sheathing material (OSB).
- Wall assemblies with an air gap (fiber cement, vinyl, stucco with 3/8 in. gap, and brick veneer) saw no sustained increase in sheathing moisture content during moisture injections.

Although moisture problems and building failures related to moisture have been seen in the field on absorptive claddings, extended high moisture levels were not observed in this study. The problems that have been experienced in residences could be due to a variety of factors: material selection, workmanship problems, elevated interior humidity conditions, increased weather exposure, and/or lack of design considerations. A more thorough effort is necessary to adequately understand moisture-related wall failures.

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