# Approach to Assessing Continuous Insulation Products


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## ABSTRACT

*More rigorous energy codes and requirements for energy-efficient construction are spurring interest in new insulation products, specifically those that provide continuous exterior insulation. New exterior insulation products, especially those that have nontraditional forms, need to be evaluated not only for basic material properties such as R-value, but also for their installed assembly performance and compatibility with other system components. This paper discusses several methods that can be used for system-level product evaluation and demonstrates the value of this approach.*

*Full-scale laboratory testing was conducted on wall assemblies constructed using two different types of exterior insulation. The exterior insulation products compared were a low vapor permeance XPS insulation and a high vapor permeance fibrous exterior insulation relatively new to the market. Evaluation methods included thermal imaging analysis using a climate simulator and structural performance testing of cladding attached to strapping that was fastened to the structure through the continuous exterior insulation. The thermal imaging analysis included side-by-side wall construction in the climate simulator and infrared thermal images taken of both the interior drywall and exterior insulation or cladding while operating the simulator in a winter climate condition. The structural assembly testing consisted of deflection measurement of both short- and long-term loading of various simulated cladding weights to the strapping, which was fastened to the structure through the exterior insulation.*

*Conducting these laboratory tests and analysis produced a more realistic in-service performance prediction of exterior insulated wall assemblies that accounts for the interaction of the various assembly components.*


## INTRODUCTION

Construction practices have evolved alongside the development of construction materials to meet the demands of the industry today. Many historical buildings were built with loadbearing masonry or solid wood, with little or no intentional insulation. Most modern enclosure wall systems employ a layered approach, with a variety of engineered materials that are designed to fulfill specific functions (such as structure, finish, water control, and thermal control) that have the advantage of lighter weight and a wider range of exterior finish and enhanced thermal and moisture performance. As part of this evolutionary change in enclosure walls, new products are being developed and deployed to provide continuous insulation, airflow control, and liquid water control.

Some amount of insulation is required in all new building projects. The amount of thermal resistance is based on the climate region for the project and the specific building or energy code in force. The thermal performance of an insulation product is defined by its resistance to heat flow, or R-value (RSI in SI). The R-value of the insulation is the most widely used metric to differentiate between individual insulation materials, although there are several other functional characteristics that should be considered. In many cases, insulation products are chosen without adequate knowledge of how the insulation will perform as part of a system with other components of the enclosure. It is important to consider system effects in order to meet specific project criteria such as price, wall thickness, R-value, and control of air, vapor, fire, noise


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etc. Standard tests are often required for compliance to building codes and standards, but in-depth research and nonstandard tests are required to predict how materials and systems interact. Systems testing is not a new concept, as manufacturers have long conducted tests to compare their products to other products, but because of the ever-increasing number of products, types of materials, and myriad combinations, systems testing is now even more important.

This paper discusses several methods that have been used to evaluate how a new continuous insulation product performed in terms of its functional requirements within a building system. The product consists of polyester-blend fibrous matt with a vapor permeable air and water barrier membrane integrated on the exterior face of the matt. The product differs from the majority of exterior continuous insulation products in that it is more flexible and so is provided in rolls that can be installed and detailed in a similar fashion to building wrap. Vinyl siding can be attached directly through the fibrous insulation; however, when heavier claddings are installed, such as wood or fiber cement claddings, the fibrous exterior insulation alone cannot structurally support cladding loads. To provide additional support, insulated battens made from plywood and XPS are first installed against the sheathing and attached to the structure. The fibrous insulation is then rolled out over top of the insulated battens, and heavier claddings are installed into the nailing strip on the battens, providing a thermal break and preventing a loss in R-value where the fibrous insulation is compressed.

Because this product differed in form from standard exterior continuous insulation products, its evaluation serves as a case history to understand the many system attributes that need to be considered as part of understanding installed assembly performance.

## FUNCTIONAL REQUIREMENTS

Depending on the individual project, there are many functional requirements an insulation product may be required to meet in addition to thermal resistance. The broad categories of functions of all products in the building enclosure can be broken into three main categories: finish, support, and control (Straube and Burnett 2005). Generally speaking, the insulation is not the intended finish, although in some cases it might be visible through an open-jointed cladding system. Some products used on the interior must perform an interior finish function (e.g., roll batts and rigid board insulation for some industrial buildings). In terms of the support function, the insulation may be required to transmit gravity loads from cladding, wind loads from the cladding, and air barrier, seismic loads, etc., from the cladding to the structure. There are four primary control-related functions: water, air, thermal, and vapor. The thermal control function is the primary function for insulation materials. Some materials can perform multiple functional requirements. For example, closed-cell spray foam could be the air, thermal, and vapor control if it is installed in the stud cavity and could be a part of the water control layer if it is installed on the exterior of the sheathing. Another example is that in some locations, polyethylene sheeting is installed on the interior as both the air and vapor control layer. There are two additional control attributes that are sometimes considerations when selecting a product for a particular application: fire spread and sound attenuation. This paper focuses on evaluation of the support and thermal control functions.

### Thermal Transport Control

The most critical function of the insulation is to resist the movement of heat energy through the enclosure. The United States Federal Trade Commission requires that R-value testing be conducted at a mean temperature of 75°F (24°C), although it does not specify a temperature difference or an orientation for the sample (FTC 2005). In the case of closed-cell foam insulations blown with special gases, long-term thermal resistance testing (as per ASTM C1303 [2015c]) is also required to determine the long-term R-value, because the R-value of these products is known to change over time. Insulation products are usually tested according to ASTM C518/ASTM C177 (2015a) material test standards at one temperature difference across the insulation product. This common procedure for measuring R-value provides the ability to compare different products but also has some disadvantages. The R-value of insulation materials changes depending on the mean temperature and, to a lesser extent, the temperature difference across the insulation. Many insulation products have a higher R-value at lower mean temperatures (because of the reduced role played by radiation transfer), but there are some materials where the R-value degrades significantly at lower temperatures. These differences are not considered in the standard reporting of material R-value. It is also important to realize that when insulation is part of an enclosure system, the enclosure does not have the same R-value as the insulation. The most common cause of this change in R-value is thermal bridging (caused by building structure [framing and other elements], fasteners, windows, etc. penetrating the insulation) and convection loops (caused by air moving around insulation). Provided the installation of the insulation layer does not allow significant air loops to bypass the product, the advertised R-value can only be realized when the insulation material is continuous over the enclosure without interruptions. It is important to realize that all insulation materials are affected in this way. The total R-value of the fibrous exterior insulation material is R-5.4 for the entire thickness (approximately 1.5 in. [38 mm]) (DuPont 2013).

### Vapor Diffusion Control

A specific level of vapor permeance may also be a functional requirement for insulation. Insulation may be specified as vapor permeable or vapor impermeable (to either increase drying or limit vapor diffusion), depending on where the insulation is located in the enclosure (closer to the interior or exterior) as well as the exterior climate, the intended indoor environment, and other layers in the enclosure system. The vapor permeance of a material is usually determined using the ASTM E96 test method. The most common tests determine how much water vapor moves across a material from 50% relative humidity to 0% relative humidity (desiccant or dry cup method) and from 100% relative humidity to 50% relative humidity (wet cup method). In some cases, the vapor permeance is the same for both conditions, but some materials exhibit different vapor permeances at the two different test conditions. For many materials, the vapor permeance will decrease with increased thickness of the material, such as foam-based insulation products for example. For the fibrous exterior insulation material being reviewed, the ASTM E-96 wet cup and dry cup results are 269 perms and 228 perms, respectively (DuPont 2013). Knowing the vapor permeance of a material will help determine climate regions and locations within the enclosure where the material may be used correctly without increasing moisture durability risk.

### Air Leakage Control

The insulation material may serve the functional requirement of an air barrier material and be part of the air barrier system in the enclosure. The airtightness of a material can be determined based on ASTM E2178 (2011b). The air permeance of insulation may be important if the insulation product is to be part of the air barrier system, but also important is the quality of the installation and the transitions between all components of the air barrier system. System airtightness can be evaluated using mock-up assemblies and testing by ASTM E283 (2012b). Mock-up assemblies can be designed to evaluate installation details such as window integration, pipe or duct penetrations, and cladding attachments. ASTM E2357 (2011c) provides a standardized assembly for air leakage evaluation. Because the product used as the example in this study had an air barrier membrane as its exterior face, it met industry and code requirements as an air barrier material. Installation practices for standard mechanically attached air barrier membranes were modified to account for the increase in product thickness. The creation of flaps allowed for shingling and sealing. Several mock-up assemblies were tested, and installation practices were developed that allowed for the system to meet industry and code assembly air leakage requirements.

### Water Control

Some insulating products used on the exterior of buildings can also function as the water control layer. This water control layer is typically installed behind a cladding that is presumed to leak rain water (i.e., a rainscreen) but which acts as the primary water-shedding layer. It is key that the water control layer be properly detailed to ensure rain water is directed back out of the enclosure at regular intervals and at key junctions with penetrations. To evaluate the ability of a product to act as a water control layer, numerous standard (such as ASTM E331 [2016e], ASTM E547 [2016f], or AAMA 508 [2014]), and nonstandard tests of the product installed in a mock-up with typical details are commonly undertaken.

### Sound Control

In some cases, insulation products are selected based on their sound attenuation or dampening characteristics. The effect on sound transmission of an individual material may be important, but airtightness levels and the combined effects of different materials will have a more significant impact on noise control.

### Fire Control

Some fire-related testing is conducted on individual materials, but many systems of materials such as roof and wall assemblies must be fire tested as complete systems before they can be allowed in construction of different residential and commercial buildings. Many common fire control standards (e.g., ASTM E84 [2016c]) recognize that assemblies will perform differently than materials considered separately, by protecting other materials in the assembly or providing paths for fire and smoke within the assembly.

### Summary

To ensure that a specified product will meet all of the necessary functional requirements for a specific project, material property and performance data can be very useful, especially when used in combination with thermal or hygrothermal modeling. However, system-level testing can confirm and demonstrate that the performance will meet the functional requirements of a project. If unique assemblies and nonstandard applications are considered, system-level testing becomes more important.

## PREDICTION OF IN-SERVICE PERFORMANCE USING MATERIAL PROPERTY DATA

Typically, evaluation of insulation performance is based on standardized material testing. This testing would include, as a minimum, determining the R-value or thermal conductivity in the ASTM C518/C177 (2015a) test and determining the vapor permeance in the ASTM E96 (2016d) test. Other tests that manufacturers commonly conduct include compressive strength (e.g., ASTM D1621 [2016b]), water absorption (e.g., ASTM D2842 [2012a]), and coefficient of linear expansion (e.g., ASTM D696 [2016a]). Individual material property testing is routinely done and is therefore relatively quick, straightforward, and inexpensive. Once the individual material properties have been identified, thermal and hygrothermal simulations of assemblies may be conducted to predict performance based on both the material properties of the several materials used in a modern enclosure and the geometry of the intended applications. Computing power has increased in the last several years, and simulations have improved in their predictions. Using material data to build a model may provide a reasonable basis for making recommendations and explaining system performance.

However, there are limitations to this approach. Individual material property testing does not take into account any of the system effects that occur when different materials are combined together, such as accurately determining the effective R-value of an assembly with different materials or accounting for air leakage. Also, performance may be affected by quality of installation or incompatibility of different products. For example, some foam plastics such as EPS foam insulation can be dissolved by some solvents. These solvents are used in solvent-extended asphalt emulsions for waterproofing as well as some other products. Simulations can address some of these issues, but these too have their own limitations. Models are easily affected by inexperienced users or incorrect material data (for example, when a generic data set is substituted for a material that does not have data available or the temperature dependent R-value may be assumed to be linear when it is not). In some situations, the factor of safety and/or risk can be inflated or deflated sufficiently that applications of that system in the real world fails. Most software packages also have inherent limitations, including the inability to accurately predict air leakage effects on R-value, condensation, and moisture accumulation. To ensure that models and simulations reflect reality and can be relied upon, measurement in the field or laboratory testing must be completed.

## MEASURING PERFORMANCE AT THE SYSTEM LEVEL

A systems approach to testing considers several aspects of performance simultaneously, instead of a single performance variable. Several test protocols are described below that illustrate the systems approach. Results from most of the tests compare a low vapor permeance XPS insulation and the high vapor permeance fibrous exterior insulation that is used as the example. These tests generally do not meet any current standardized test method. They were developed to meet a need for manufacturers to answer industry questions and perceptions or compare their products to other products in a way that is more representative of how the product will actually be used and installed. Some of the tests are more qualitative and some are more quantitative in nature, but each demonstrates some aspect of insulation system performance.

### Deflection Testing

There are many questions, and even more perceptions, in the industry regarding the attachment of cladding through thick layers of exterior insulation. These questions began with the trend towards effective R-values of wall assemblies and the application of continuous exterior insulation to minimize thermal bridging. It is common to install vertical strapping or furring on the exterior of the insulation attached back to the wood frame structure and then attach the cladding to the vertical strapping. Strapping or furring strips are usually 1 × 3 nominal lumber or, in some cases, plywood sheathing cut into strips of the desired width and required thickness. In the case of the fibrous insulation considered here, insulated battens were provided as furring to compensate for R-value loss due to compression of the low-density fibrous insulation material. Potential deflection of the cladding is a system effect of the cladding, strapping, insulation type, fastener type, and attachment method, which is why it is critical to test the assembled wall. There are currently no standard test methods for determining the deflection of cladding using the entire wall assembly.

A test method was developed to answer questions regarding potential deflection or movement of cladding attached through the exterior insulation to the structure to minimize the thermal bridging through the insulation. To interpret the deflection data, some typical weights of cladding were calculated based on product manufacturer documentation to estimate the approximate square foot weight of each cladding type. In some cases, it was necessary to use a range of weights, as it was found that similarly advertised products varied in weight. The weights are shown in Table 1. Deflection testing was completed in the laboratory on a short-term basis and a long-term basis. Long-term testing was also completed in an outdoor environment under full exposure to the elements.

### Laboratory Short-Term Deflection Testing.

To conduct the testing, a 4 × 8 ft (1.2 × 2.4 m) wall frame with 16 in. (406 mm) stud spacing was securely fastened to a concrete block wall in the laboratory. The 7/16 in. (11 mm) OSB sheathing was installed over the framing. The insulated battens (plywood nailer on an XPS base) for the exterior insulation system were installed through the framing into the structure with 3 in. (76 mm) framing nails (11 in. [280 mm] o.c. vertically). The exterior insulation system was installed over the battens, and 2 × ½ in. (50 × 12.5 mm) plywood strapping was installed through the insulation to the battens, compressing the insulation between the strapping and the batten. A 4 × 8 ft (1.2 × 2.4 m) cladding panel was installed to help distribute the point load at the bottom of the wall assembly to each of the three strapping pieces, so the force was equally applied. The cladding was attached with 2 in. (50 mm) nails through the insulation into the wood surface of the battens. The steel straps on the exterior were only attached to the face of the cladding and not to the strapping.

**Table 1. Approximate Cladding Weights**

| Cladding Type | Typical Mass Density, psf | Equivalent Weight for 4 × 8 ft Test Panel, lb |
|---|---|---|
| Vinyl siding | 0.6–1.0 | 20–32 |
| Wood siding | 1.0–1.5 | 32–48 |
| Fiber cement siding | 3–5 | 96–160 |
| Cement stucco | 10–12 | 320–384 |
| Adhered stone veneer | 17–25 | 544–800 |

This report only includes one comparison between similar wall assemblies with XPS exterior insulation and fibrous exterior insulation (Figure 1), although the initial research program also investigated different lengths of fastener without strapping, as well as a plastic rainscreen strapping product, all with fibrous exterior insulation.

Both of the comparison walls used 0.095 in. (2.4 mm) gauge galvanized siding nails to attach the cladding to the strapping 8 in. (203 mm) o.c. vertically on each row (three vertical rows) of strapping, for a total of 39 fasteners.

A 4000 lb (18 kN) capacity hydraulic ram was used to apply force to a metal angle in connection with the bottom edge of both metal strapping pieces attached to the surface of the cladding. To measure the applied force, a 1000 lb (4500 N) strain gauge load cell (with ±0.4 lbf rated accuracy) was placed between the angle and the ram (Figure 2).

Deflection gages (with a resolution of 1/1000 in. [0.025 mm]) were used to measure the movement of the wall sheathing and cladding on both the left and right side. Measurements of the framing were also taken to verify that the movement occurred between the sheathing and the vertical strapping.

Loads were applied in increments of 100 lb (45 kg) between 100 lb and 1000 lb (approximately 45–450 kg). The four deflection readings were recorded at each increment. Each load increment was applied over about 30 to 60 seconds, and the readings taken within 30 seconds. All of the tests were conducted three times on the same test specimen. The wall was loaded to 1000 lb (454 kg), unloaded of all weight, and reloaded two more times to 1000 lb (454 kg). The analysis of the effect of loading only compares the first test for each construction type, but the second and third test can be useful to show any permanent deflection in the wall assembly following a high loading event. For the test wall results in Figure 3, the total deflection at 1000 lb (453 kg) was approximately 0.03 in. (0.8 mm). After the initial load was removed in each of these tests, the wall returned to approximately 0.015 in. (0.4 mm), so there was a permanent deformation after the load

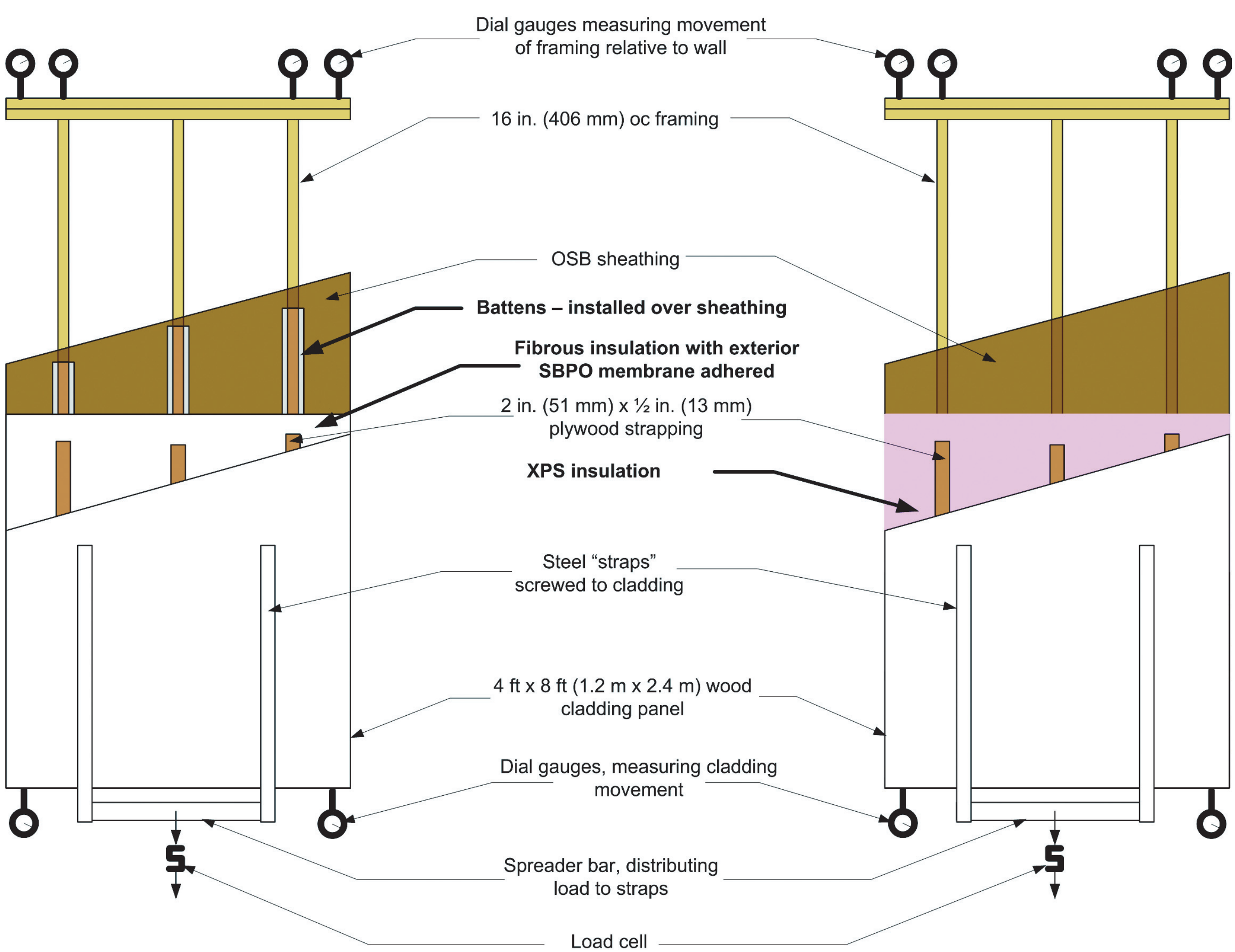


***Figure 1*** *Schematic construction drawing of the fibrous insulation and XPS wall assemblies for short-term deflection testing.*

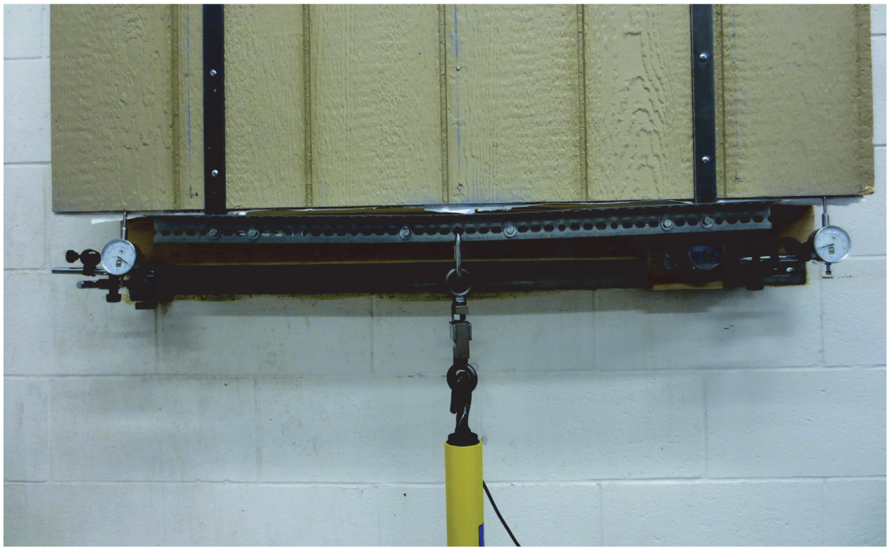

*Figure 2* *Short-term deflection test setup and measurement.*

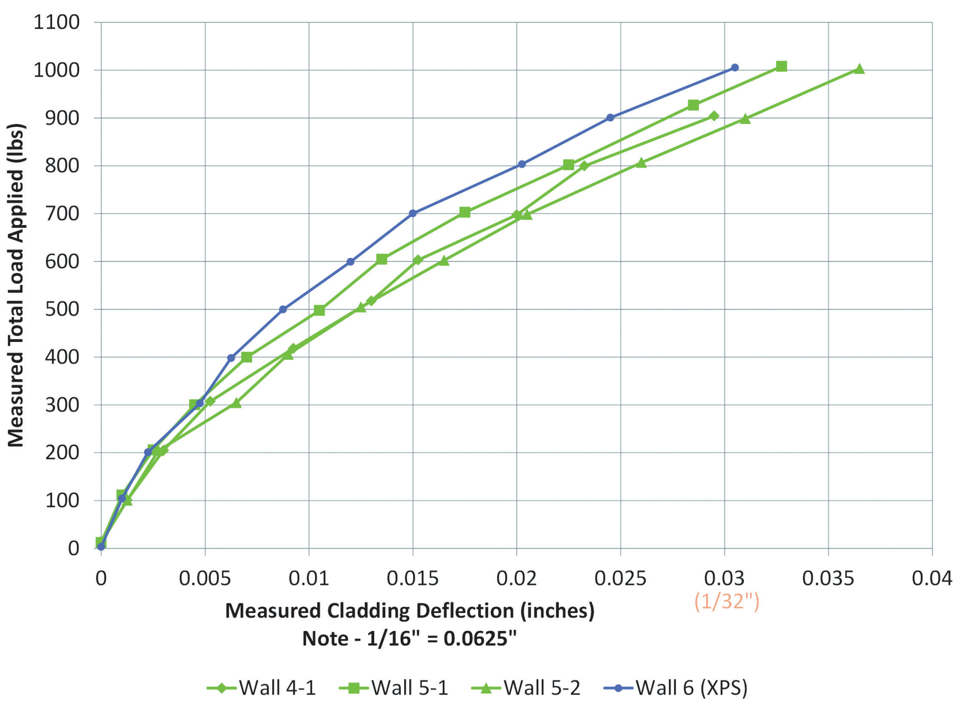


*Figure 3* *Short-term deflection comparison data.*

of 0.015 in. (0.4 mm). Following the second loading, the wall returned to the same location (0.015 in. or 0.4 mm) for each of the tests, showing that there was no further permanent movement once the initial loading had settled the wall assembly.

Experimental variables in the short-term deflection testing included fastener type, length and spacing, insulation type and thickness, and strapping type. During construction of test wall assemblies, products from a local hardware store were used wherever possible, and specialized fasteners and materials were not used, to be able to determine the practical worst case scenario that may be constructed.

The comparison results of the wall assembly with XPS continuous insulation (blue line), and fibrous exterior insulation (green lines) in Figure 3 shows almost no difference in deflection results. At 1000 lb of total force (31 lb/ft$^2$), the deflection in all of the assemblies was approximately 0.03 or 1/32 in. (0.76 mm). The fibrous insulation wall assembly test was repeated three times to show the repeatability of the measurements. All other variables were the same for the comparison tests in Figure 3.

Based on the initial short-term deflection testing, questions arose regarding the effects of a long-term sustained loading of the cladding and the possible deflection results that would occur (Smegal and Straube 2011). Long-term deflection testing for at least 12 months was conducted in response to these industry questions.

### Laboratory Long-Term Deflection Testing

Long-term deflection testing has been conducted on many insulation materials to address the questions about long-term loading of cladding weights attached to strapping or furring strips. The results of the fibrous exterior insulation long-term testing was conducted in a similar way so that comparisons with previous test results were possible. A wood-framed wall section measuring 16 in. (406 mm) wide and 8 ft (2.4 m) tall with a single vertical stud in the center was securely fastened to a concrete block wall in the lab. The 7/16 in. (11 mm) OSB was attached to the framing, and an insulating batten was installed into the framing with 3 in. framing nails spaced 11 in. (280 mm) o.c. vertically. The fibrous insulation was installed, and a 2 in. (51 mm) wide ½ in. (13 mm) thick plywood strapping was installed the full height of the test wall. Cladding was installed through the strapping to the wood layer of the batten with 2 in. (51 mm) 0.095 gauge galvanized ring shank nails spaced 8 in. (203 mm) vertically. A metal strap identical to the short-term testing was installed against the cladding and only attached to the cladding, so that the long term load was held by the cladding and transferred to the structure through the cladding attachment fasteners. The XPS long-term deflection test was part of a different research project, and the load was applied directly to the strapping, because no cladding was installed on the test assembly. However, this is not expected to change the results for the XPS wall assembly, because, due to the rigidity and compressive strength of the foam insulation, the load would be transferred directly from the cladding to the strapping and to the surface of the insulation and fasteners.

A weight of 210 lb (almost 100 kg) was attached to a single strapping member attached through different exterior insulations (shown in Figure 4) simulating a weight of 20 psf, greater than relatively heavy standard three-coat cement stucco (Table 1). The perception with long-term deflection is that it is only a concern with heavy claddings, which is why a weight of 20 psf was chosen. Past research conducted with a 4 psf weight indicated there was no long-term deflection concerns. This weight was suspended from the strapping for more than a year, and deflection gauge readings were taken periodically.

***Figure 4*** *Long-term deflection testing weights.*

Initial observations from the long-term laboratory deflection testing suggested there was a measured deflection response to changes in laboratory relative humidity and temperature conditions. The movement of the wood-based furring and framing of the wall system is assumed to explain these observations. The other observation was that with a 20 psf cladding weight, there was very little long-term deflection following the immediate initial deflection measured when applying the loading of the weight on the wall (see also Baker and Lepage 2013). Typically, the heavier cladding systems are also not applied in a single coat; they are applied in layers and the system has the opportunity to adjust between each layer.

Figure 5 shows long-term deflection data for two assemblies with exterior fibrous insulation and one assembly with exterior continuous XPS insulation. The XPS and fibrous insulation wall assemblies were not conducted simultaneously and were exposed to slightly different laboratory conditions during the testing. There was a correlation between the movement of the XPS wall assembly to the fluctuations in interior relative humidity, although the changes in deflection were very small. This occurs because wood materials shrink and expand in response to changes in the surrounding moisture conditions; so, as the relative humidity in the lab changes, there will be a response in all wood materials, and this shows up as a change in the deflection of a wood-framed test assembly. The entire $y$-axis of the plot spans a total of only 1/32 of an inch. For this comparison, the first hour of testing was not plotted; so, the immediate initial deflection was removed and the long-term effects of the 20 psf cladding emphasized. The long-term deflection results in Figure 5 show approximately the same deflection for the XPS exterior insulation wall assembly and the fibrous insulation exterior wall assembly.

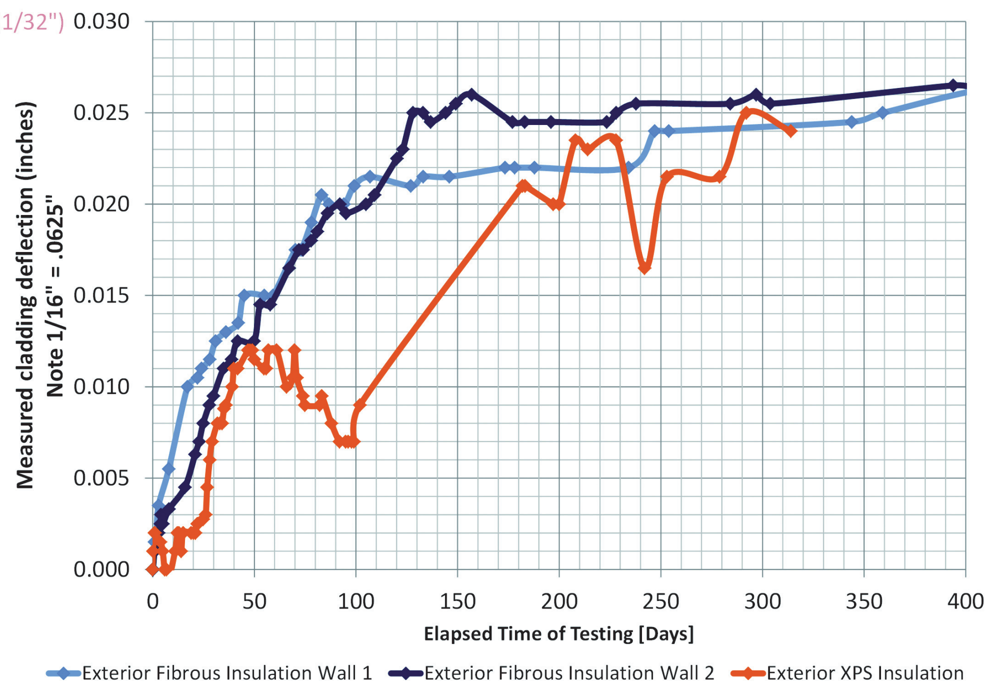


***Figure 5*** *Long-term deflection comparison data excluding initial deflection.*

Based on the small changes in deflection due to changes in laboratory RH, it was concluded that long-term deflection should be conducted fully exposed to the weather outdoors for the period of a year. The goal was to measure the deflection as a result of both moisture and temperature fluctuations of the assemblies and investigate if the cyclic nature of weather (wind, temperature, and humidity) would cause more deflection than testing in the protected lab environment. This testing was conducted, but is not included in this paper; more information can be found in previously published reports (Baker 2014).

Deflection testing demonstrates the measured deflection with a specific set of installation criteria, and, by modifying the experimental criteria, the effects on deflection can be determined. Typically, fewer parameters are tested during long-term testing because of the space required for each test over a long period of time. It is difficult to predict the deflection based only on the individual material testing because the interactions between the materials, such as friction effects between the layers and effects of moisture, are not included in material testing. Deflection testing may also be used for quantifying the impact of construction defects, such as missing fasteners and screw attachment to the sheathing rather than the framing, for example.

## Limitations of Deflection Testing

Although deflection testing provides valuable information regarding the load capacity and stiffness of attaching cladding through layers of continuous insulation, there is no agreement on how much deflection is allowable. Although lap siding systems can tolerate relatively large movements without problems, the allowable settling and movement of rigid cladding systems, such as three-coat cement stucco, has not been determined. It is unclear how much movement hard-coat stucco can experience before surface cracking occurs. Although adhered stone veneers are heavy, and should generate the most deflection, even when cracks occur they are not as visible because the surface is very irregular with both mortar and stone (instead of smooth and continuous as with stucco). This will act to camouflage any small cracks that might occur. If cracks are large enough, they may increase the absorption rate of water into the cladding. There are decades of experience with millions of buildings that show the normal movement of wood structures (due to seasonal expansion and contraction due to temperature and humidity effects) can be accommodated successfully. The deflection at sawn timber rim joists are significantly more than the deflections measured in the tests reported. Nevertheless, the industry would be well served by better allowable design criteria for cladding movements.

## Thermal Imaging Analysis

Infrared thermal imaging analysis is another method that can be used to determine the relative performance between two different wall assemblies. It has the advantage that it can visually demonstrate spatial performance differences of relatively high resolution (i.e., fractions of an inch). Because the thermal performance of a wall assembly is a function of the interrelated performance of all components, infrared imaging of enclosure thermal performance requires all of the components to be assembled in a realistic manner and exposed to air pressure differences to ensure air leakage is accounted for. As with many other methods, a comparison between two samples provides a much more reliable and accurate means of measuring performance.

As an example of the use of infrared imaging, two walls were constructed in a climate chamber capable of maintaining constant interior and exterior temperatures as well as imposing air pressure differences. The similarities between the two walls were: taped interior drywall, 2 × 4 wood framing at 16 in. (406 mm) o.c., and R-13 fiberglass cavity batt. One wall had R-5 of continuous XPS insulation with taped seams installed to the manufacturer's specifications. The other had R-5 continuous fibrous insulation that included a spun bonded polyolefin (SBPO) exterior air and water control layer. The walls were thermally isolated from each other to avoid any heat transfer. Each test wall consisted of a rim joist section with short floor joists, subfloor, and ceiling drywall. An electrical outlet was installed in each wall in an identical manner. All of the wall framing was sealed to the edge of the climate chamber to stop the air from bypassing the wall assembly during the pressurization and depressurization tests. Because the battens are not used for vinyl siding installations, they were not used in this side-by-side comparison. Another wall was constructed that did use the insulated battens for a different thermal comparison.

Thermal imaging of the test pairs was conducted following approximately 24 hours of conditioning at the interior and exterior setpoints of 72°F (22°C) and 19.5°F (–7°C), respectively. Thermal imaging was first conducted with no applied pressure difference across the wall, then with positive 10 Pa, and finally with negative 10 Pa. In real buildings there is often a pressure induced across a wall either from wind effects, natural stack effects, or internal HVAC systems. The pressures across low-rise residential enclosures are typically 3 to 10 Pascals. To provide an easy-to-control and meaningful signal, the pressure on the test walls was maintained using a blower connected to the cold side of the climate chamber to both pressurize and depressurize the climate side. A Magnahelic® differential pressure gauge was connected to a pressure tap on the climate box to show the pressure in the climate chamber.

On the 2 × 4 R-5 XPS wall (Figure 6), the average of the temperatures between the studs is 71.3°F (21.8°C) and over the studs is 70.4°F (21.3°C). On the 2 × 4 wall with R-5 fibrous exterior insulation (Figure 7), the average of the temperatures between the studs is 71.7°F (22.1°C) and over the studs is 70.9°F (21.6°C). During this test, the measurements showed very small but consistently warmer surface temperatures both on and between the studs of the continuous R-5 fibrous insulation wall assembly compared to the R-5 XPS wall assembly. These results imply that the two approaches to continuous insulation provide similar performance, with the fibrous roll insulation performing slightly better. The results may be caused by the slightly higher C518 testing results of the fibrous insulation (R-5.4) compared to XPS (R-5.0).

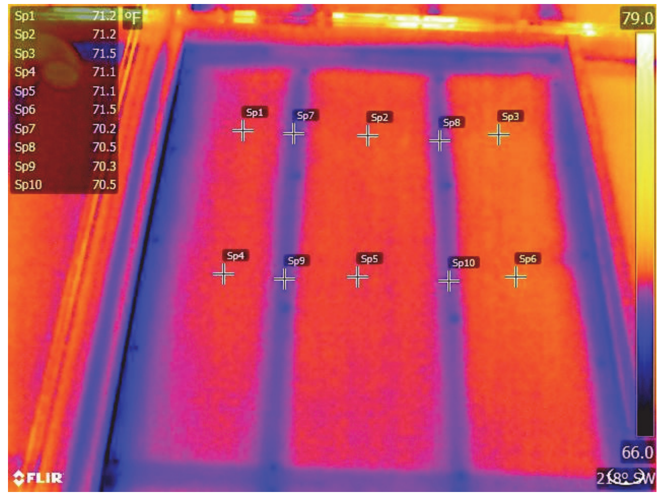


***Figure 6*** *Drywall surface temperatures of 2 × 4 framed wall with continuous exterior R-5 XPS.*

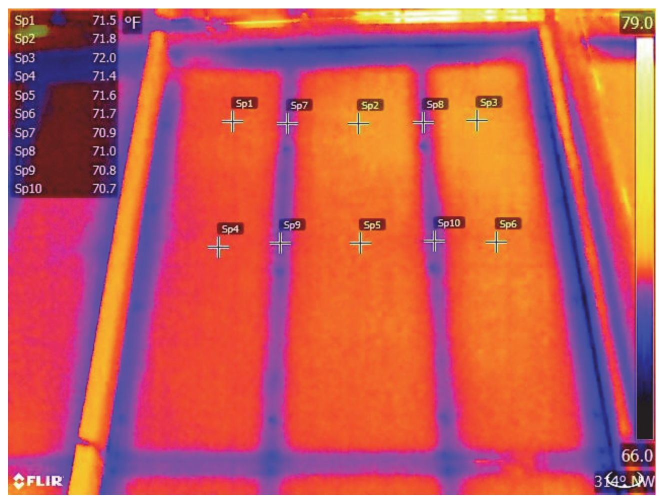


***Figure 7*** *Drywall surface temperatures of 2 × 4 framed wall with continuous exterior R-5 fibrous insulation.*

## Guarded Hot Box Testing

RDH Building Science Laboratories in Waterloo, ON (formerly Building Science Consulting Inc.), in partnership with Building Science Corporation, has conducted guarded hot-box testing on many types of insulation and wall assemblies based on ASTM C1363 (2011a) with some modifications (BSC 2015). The modified test measures the overall R-value of a 12 ft wide by 8 ft high test sample. Framed walls have been tested that include all of the enclosure construction material from the interior drywall to the exterior vinyl siding. The R-value that is calculated is based on the heat flow through the wall assembly and all of its components, such as framing, exterior insulation, air leakage, and temperature-dependent conductivities of the materials. The standard RDH protocol employs numerous outdoor air temperature set points with a fixed realistic indoor temperature to allow for the temperature dependence of all components (including shrinkage and swelling of joints) and insulation materials to be assessed. Example results from two walls are plotted in Figure 8 (Schumacher et al, 2013). The assemblies consisted of all enclosure materials including drywall, wood framing, OSB sheathing, housewrap, and vinyl siding. One of the test walls had R-5 of exterior XPS insulation. The walls shown in Figure 8 were tested in a "sealed" condition, with a thin layer of adhered plastic film on each side air sealing both sides of the wall assembly, eliminating air leakage from either side. The airtightness was confirmed with tracer gas testing. Other testing has specifically looked at the effects of air leakage on the effective R-value of different wall assemblies.

These types of impacts on advertised R-value were expected based on thermal simulations and physics, but, until recently, there was almost no measurement results on full-scale wall assemblies that are able to measure the heat loss/gain through the air transfer system when applying controlled pressures to the full-scale wall assembly.

This testing has reinforced that critical factors for insulation effectiveness include the amount of thermal bridging, temperature-dependent effects, and, in other testing, the amount of air leakage across the assembly. These factors can significantly impact both the thermal and moisture performance of an enclosure assembly but cannot be determined by any individual material tests.

### Full-Scale Field Testing and Moisture Monitoring

All of the previous assessment methods investigated the thermal impacts of the assembly and its components. It is often more important to understand the moisture behavior of the wall assembly to predict durability and common in-service problems, such as mold. Hygrothermal modeling, material testing, laboratory subassembly testing, climate chamber exposure, and field exposure are all methods available to assess moisture performance. Realistic full-scale heat and moisture testing of an assembly exposed to a real exterior climate with controlled interior conditions over at least one year provides a robust method. Test huts are often preferred over the use of whole buildings because test hut walls can be stressed to failure with moisture without the cost of replacing whole buildings (Straube et al. 2002).

Moisture performance is more difficult to predict than thermal performance, because it depends on a greater number of physical properties as well as the moisture conditions on the interior and exterior of the wall assembly in combination with all of the thermal considerations.

Figure 9 is a photo of the exterior of a series of residential and commercial test walls during construction at a test hut in Vancouver, BC. The test walls have exterior insulation (some are covered by a drainage plane or UV barrier). By instrumenting the walls, and monitoring them under normal operating conditions, the side-by-side performance of the insulation systems can be measured and compared on all four orientations. In some cases, water is injected into the wall assemblies in a controlled manner to simulate a rain leak through the

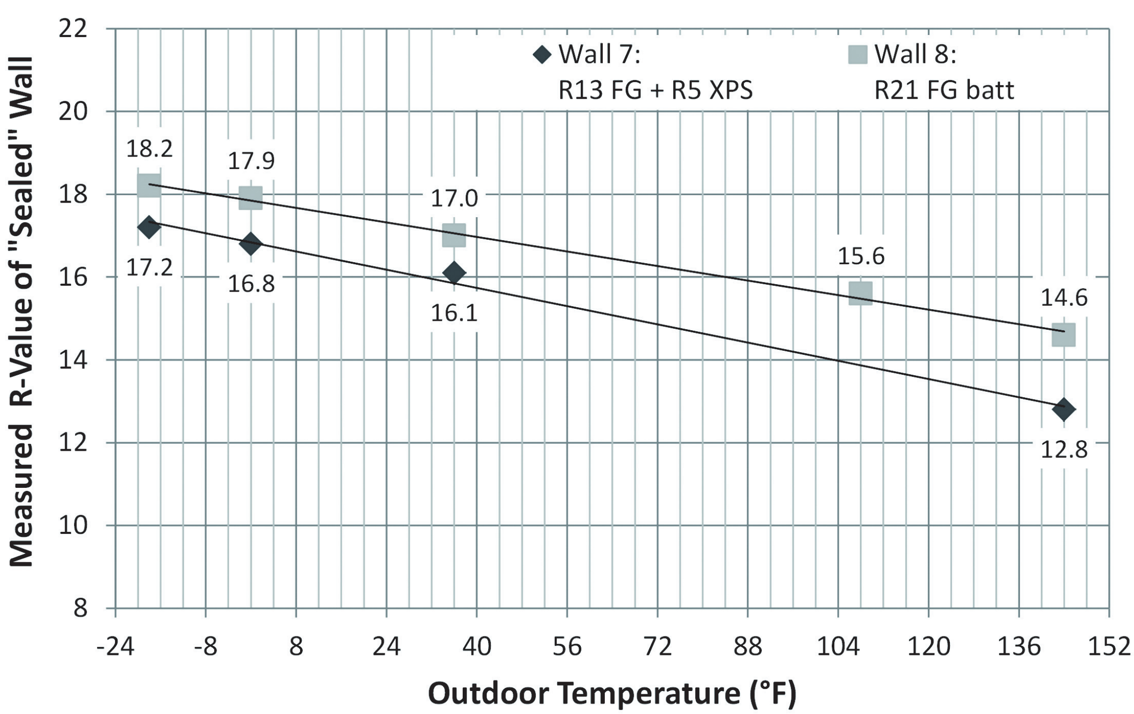


***Figure 8*** *Results of guarded hot-box testing of two wall assemblies (Schumacher et al. 2013).*


***Figure 9*** *Full-scale field test assemblies.*

enclosure or to add stress to the system. In other applications indoor or outdoor air can be injected into the wall system at a known rate to simulate an air leak into the enclosure and measure the system's response.

The two comparison walls included in the test hut research relevant to this study are two residential wood-framed wall assemblies, one with exterior R-5 exterior XPS and one with R-5 of exterior fibrous insulation with insulated battens. The common construction variables in the wall assembly include the following: painted drywall, 2 × 6 wood framing with R-21 Kraft-faced fiberglass batt, 7/16 in. (11 mm) OSB sheathing, 2 × ½ in. (51 × 12 mm) wood strapping, and fiber cement siding. Both wall assemblies consist of an SBPO membrane outboard of the exterior insulation as the air and water control layer. The only difference in the comparison walls was the type of exterior insulation.

Two wood-framed test walls, one with R-5 exterior XPS insulation and one with R-5 exterior fibrous insulation, were compared in the Vancouver test hut. Figure 10 shows the measured OSB sheathing moisture. The red dashed lines indicate two instances when a controlled volume of water was injected into a controlled location on the exterior of the sheathing between the sheathing and the exterior insulation. The moisture content measurements shown in Figure 10 are measured at two depths in the OSB sheathing immediately adjacent to the wetting system on the north orientation. It can be seen that the fibrous insulation with the highly vapor-permeable air-water barrier facing (green line) allows the sheathing to dry much more quickly than the comparison wall (red lines), both in the summer and the fall. The drying rates are a direct result of the material properties of the exterior insulation layers, as anticipated.

This means that if there were a leak beyond the exterior insulation at a window, or other penetration, a higher vapor permeance fibrous insulation would allow the water to dry out, decreasing the moisture in the OSB sheathing much more quickly than a lower vapor permeance XPS insulation.

With measurement data such as this from field test hut monitoring, it may be possible to correlate measured data, including the interior and exterior conditions, to results from hygrothermal simulations, although this has not been done yet.

## CONCLUSIONS

Standardized material tests are a good starting point for a new product to establish comparison criteria with other accepted building materials. It is generally necessary to measure material characteristics such as vapor permeance and R-value for building code compliance. These properties are useful to help predict performance and to provide material property data for hygrothermal simulations as well as marketing. However, systems testing is required to understand performance under more realistic installed conditions and to compare predicted performance to measured performance. There are currently fewer standardized tests for assemblies (e.g., ASTM C177 [(2015a]; ASTM C1363 [2011a]; ASTM E283 [2012b]; ASTM E331 [2016e]), especially for insulation

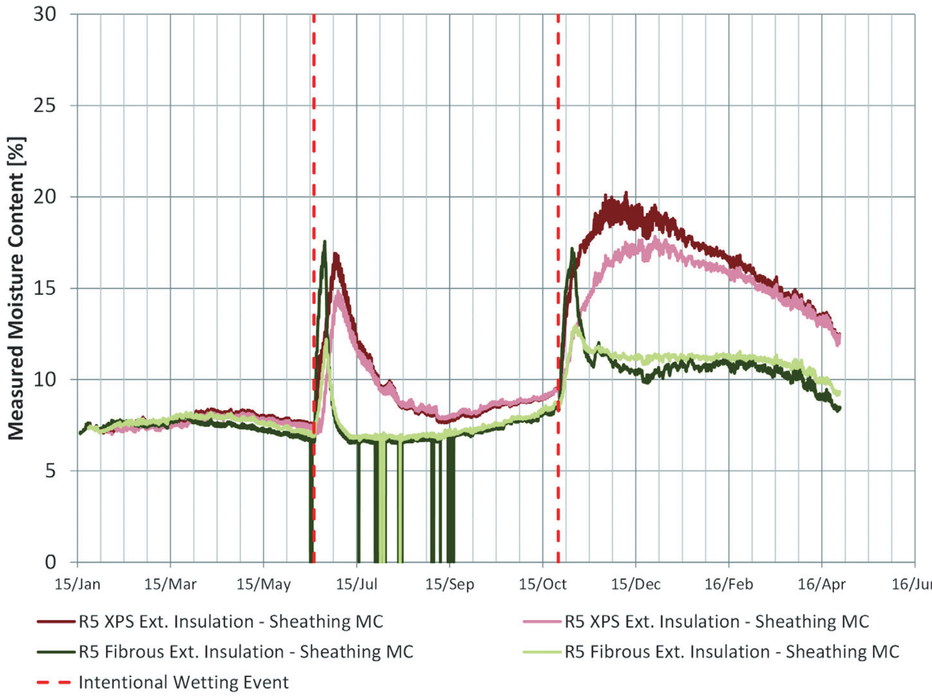


***Figure 10*** *Example full-scale wall performance comparison graph.*

products. However, this may change as building codes focus more on effective R-values and U-factors. In the meantime, nonstandard tests can also be developed and used.

The example system testing of the product used throughout this paper showed that the relatively new R-5 fibrous exterior insulation performed very similarly to the industry-accepted and widely used R-5 XPS. In the short- and long-term deflection testing, the flexible fibrous insulation system with insulated battens had essentially the same amount of deflection as the XPS wall assembly, because the fibrous insulation was compressed at the battens and behaved more like a rigid material. In the thermal imaging assessment, both test wall assemblies had very similar interior surface temperatures, indicating that the air and vapor permeable fibrous insulation performed as well at insulating the exterior of the wall assembly as the XPS insulation. During the field testing of the full-scale wall assemblies, it was demonstrated that the R-5 fibrous continuous insulation performed very similarly to the R-5 XPS under normal operating conditions in terms of measured sheathing moisture content and moisture-related durability of the wall assembly. However, during intentional wetting of the walls when water was trapped intentionally between the exterior surface of the sheathing and the exterior insulation, the fibrous continuous insulation wall assembly allowed faster drying, as demonstrated by the decreasing measured sheathing moisture content.

Based on the wall systems testing results from both the laboratory and field tests that were conducted, it was shown that the structural, thermal, and moisture performance of the exterior fibrous insulation is similar to the results of the XPS wall assembly even though their individual material properties are quite different from each other. This shows the benefits of testing systems or assemblies using tests that more closely simulate real world conditions.

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