Hygrothermal Simulation: A Tool for Building Envelope Design Analysis

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Abstract

Is it possible to gauge the risk of moisture problems while designing the building envelope? This article provides a brief introduction to computer-based hygrothermal (heat and moisture) simulation, shows how simulation can be useful as a design tool, and points out a number of important considerations regarding model inputs and limitations. Hygrothermal simulation allows a designer to predict the moisture and temperature conditions that might occur within a building envelope assembly over time. This type of analysis can improve the understanding of how the building envelope responds to the interior and exterior environment and can help identify potential moisture performance problems. The article briefly discusses the relationship between hygrothermal simulations and ASHRAE Standard 160-2009, *Criteria for Moisture-Control Design Analysis in Buildings* (ASHRAE 2009). The article concludes with simulation examples using wood-frame construction and cross-laminated timber construction to demonstrate the usefulness of hygrothermal analysis in the design of wood buildings.

Introduction

Avoiding moisture problems is a key consideration in building envelope design. Dampness in buildings has been linked to health problems and is the top category for construction litigation claims. Although moisture problems are often a result of improper construction, building operation, or maintenance, some moisture problems stem from poor design, and fixing moisture problems is much more expensive after construction than during the design process. What tools are available to designers to avoid such problems?

Moisture performance is a multi-faceted issue; in a qualitative sense, desirable performance is characterized by a balance between moisture entering and leaving a building component without resulting in damage or mold growth. This means limiting moisture accumulation as well as providing some degree of "tolerance" such that assemblies have the ability to dry out if wetting occurs (either during construction or service life). But how much moisture tolerance is needed? To design for this balance, a *quantitative* estimate of the rates of wetting and drying is needed. Hygrothermal analysis can provide such an estimate and takes moisture performance to a *quantitative* level.

Hygrothermal simulation allows a designer to predict the moisture and temperature conditions that might occur within a building envelope assembly over time. Such analysis can improve the understanding of how the building envelope responds to the interior and exterior environment and can help identify potential moisture performance problems. Although hygrothermal simulation is commonly used in research and forensic investigations, this article focuses on design analysis. The purpose of this article is to give the reader a sense of what can be gained from hygrothermal simulation as a design tool, to alert the reader to a number of important considerations regarding model inputs and limitations, and to illustrate the usefulness of hygrothermal simulation with brief examples for wood-based building envelopes.

When Is Hygrothermal Simulation Necessary?

Judgment is required to determine whether a particular design requires hygrothermal analysis. There may be no need for analysis when ample experience exists with a given type of building envelope assembly in a given location. However, many aspects of design and construction are changing: energy code requirements, green building standards, new building materials and systems, and new methods of construction. It is important to consider how these changes affect moisture performance. Ideally the designer would have information on the performance of a proposed assembly based on testing or field experience; however, such information is often lacking.

Hygrothermal analysis methods can vary widely in the physical phenomena that are included. On one end of the spectrum are simple steady-state models, such as the traditional dew point method, that include only heat conduction and vapor diffusion with constant material properties; on the other end are sophisticated computer models that include transient heat, vapor, liquid, and air transfer in as many as three dimensions, with variable material properties and detailed descriptions of phenomena such as airflow and wind-driven rain.

The dew point method and its limitations are described in the ASHRAE Handbook—Fundamentals (ASHRAE 2013) and TenWolde and Bomberg (2009). The method relies on steady-state heat flow and vapor diffusion calculations to determine whether the vapor pressure exceeds the saturation vapor pressure at any location within the assembly. The dew point method has many significant limitations. Moisture storage in hygroscopic materials such as wood is neglected, and all moisture transfer mechanisms other than vapor diffusion are excluded, even though those mechanisms are known to dominate moisture transfer in many cases. That is, the method does not address wind-driven rain absorption by cladding materials, capillary water transport, heat and moisture transfer by air movement, effects of solar radiation, or the dependence of material properties on local temperature and moisture content.

Over the past three decades, many detailed computer models have been developed to simulate temperature and moisture conditions in building envelope assemblies over time. Such models perform transient calculations, typically reporting hourly values. Further information on some advanced hygrothermal models can be found in Hens (1996) and ASTM Manual 40 (Trechsel 2001). Commonly used software packages include WUFI Pro, hygIRC, and Delphin. It should be noted that use of hygrothermal computer software requires training and experience in selection of input values and interpretation of results.

Hygrothermal Loads

The important concept of "load" is used in hygrothermal analysis in the sense of a burden or demand on the building; the response of the building to the loads can be analyzed, and the performance can be judged to be acceptable or unacceptable (TenWolde 2011). Hygrothermal loads are analogous to loads considered in structural analysis (e.g., gravity and lateral loads) and to heating and cooling (sensible and latent) loads in mechanical system design. Hygrothermal loads include initial moisture levels in building materials; indoor temperature and humidity levels; outdoor conditions such as temperature, humidity, wind, rain, and solar radiation; and air pressure differences across the building envelope.

Although hygrothermal simulation tools have become more sophisticated and able to accurately predict moisture and temperature conditions when compared with validation experiments, relatively little attention has been paid to the choice of appropriate inputs and loads for design purposes. This may not be an issue when using these tools in forensics to analyze a failure of an existing building because only the data for conditions during the period before the failure are needed (though obtaining accurate and sufficient data is difficult enough). However, the choice of appropriate input values is even more uncertain when the analysis is used for design purposes before the building has been built and before actual loads can be measured. These considerations suggested a need for a standardized approach to establish moisture design loads.

ASHRAE Standard 160

In January 2009, the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) published a new standard, ANSI/ASHRAE Standard 160-2009, entitled *Criteria for Moisture-Control Design Analysis in Buildings* (ASHRAE 2009). Work on the standard began in 1996 and arose from the increased use of computer-based hygrothermal analysis tools and the concerns discussed above.

Another reason for creating this standard is that many recommendations and rules for moisture control are not based on a set of consistent underlying assumptions. The need for various moisture control strategies or design features often depends on what indoor or outdoor conditions are assumed. For instance, a computer analysis by Tsongas et al. (1995) of moisture accumulation in a wood frame wall in Madison, Wisconsin, showed that the need for including a vapor retarder in the design completely depended on the selection of indoor humidity. Many other studies have consistently shown that simulation results can be rather sensitive to the assumed loads (Ojanen and Kumaran 1992, TenWolde and Walker 2001, Karagiozis et al. 2007). The level of indoor humidity is equally important when considering the risk of condensation on windows, the risk of mold growth on wall surfaces, or the need for attic ventilation. Thus, the choice of input values for a design analysis is critical. Whether a design analysis will show acceptable or unacceptable performance of a particular design or moisture control strategy largely depends on the design loads operating on the building.

It is widely accepted that structural building design should be based on reasonable assumptions for structural design loads. To the extent feasible, ASHRAE Standard 160 introduces an analogous approach for moisture design. As with structural design loads, moisture design loads should be more severe than average loads. An international consensus has emerged that moisture design analysis should be based on loads that will not be exceeded 90% of the time. ASHRAE Standard 160 has adopted this approach whenever feasible.

TenWolde (2001) showed how the use of a moisture design standard such as ASHRAE Standard 160 might have alerted manufactured home builders to the potential of widespread decay of plywood sheathing that occurred in the mid-1980s in a group of manufactured homes in the Midwest. The article also shows how the use of the standard could have led to the solution and prevention of problems that occurred and might have circumvented a lot of the disagreements and litigation that took place following the discovery of the building failures.

In summary, the standard is intended to bring moisture control out of the realm of purely prescriptive measures and turn building moisture design analysis into a performance-based procedure, with the potential for greater flexibility and a better ability to incorporate new designs and building materials. In addition to uniformity of design assumptions, the standard also seeks to make the moisture design analysis procedure more transparent by requiring documentation of the assumptions, material properties used, and other choices made for the analysis. A recent summary of the standard was written by TenWolde (2011). Certain key aspects of the standard are discussed in the following sections. ASHRAE is continuing to make improvements and changes to the standard. Already three major changes (Addenda a, b, and c) have been published since the standard was published in 2009, and more will undoubtedly follow. These Addenda can be downloaded free of charge from www.ashrae.org.

Modeling Considerations

Building Envelope Assembly

The first step in a typical hygrothermal analysis is to define the assembly (i.e., an exterior wall, roof, or other type), its orientation, and its boundaries. This typically involves simplification into a one- or two-dimensional representation. Figure 1 shows a wood-frame wall assembly that will be analyzed as an example using one dimension, corresponding to a line through the insulated cavity. The various material layers are identified in the figure. Similarly, Figure 2 shows an example of a cross-laminated timber (CLT) wall assembly that is also modeled in one dimension. Some cases may require use of two dimensions, such as corners, roof-wall intersections, and floor-wall intersections.

Physical Phenomena and Material Properties

Transient hygrothermal models generally include coupled heat and moisture transfer. At the material level, a number of properties can be specified, such as thickness, bulk density, specific heat (heat capacity), thermal conductivity, moisture storage (sorption and suction isotherms), vapor permeance or permeability, liquid water diffusivity or conductivity, and possibly porosity, capillary saturation, maximum saturation, and airflow permeability. Certain properties may be specified as functions of moisture content (or relative humidity) and temperature (e.g., vapor permeability, thermal conductivity). Models generally include heat and moisture transfer coefficients for the interior and exterior surfaces as well as short-wave (solar) radiation absorptivity and long-wave (infrared) radiation emissivity.

Most models typically do not include airflow, though there are exceptions. Some models include the effect of cladding ventilation, which can be an important drying mechanism. Air leakage through insulated building envelope assemblies can be an important moisture transfer mechanism, especially for lightweight wood-frame cavities with low-density insulation (Straube and Burnett 2005, Glass and TenWolde 2007). Simulating air leakage in a realistic manner is difficult because the flow paths through building envelope assemblies are three-dimensional and difficult to define, and appropriate design air pressure boundary conditions are not easily established. Nevertheless, simplified models have been developed that can be useful for comparing relative performance of different assemblies. In such models, deposition of water vapor carried by air leakage is represented by a moisture source at a selected location in the assembly. The idea is that inclusion of the effect of air flow, even in such a simplified form, provides an extra safety factor in the design.

Initial Moisture Conditions

Some building materials, such as concrete, wet-spray cellulose insulation, and wood, may contain large amounts of moisture at the time of enclosure. Little quantitative information is available, and actual conditions likely vary substantially. ASHRAE Standard 160 accounts for this initial moisture load by prescribing high initial moisture contents for those materials, unless specific plans have been included in the construction cycle to dissipate

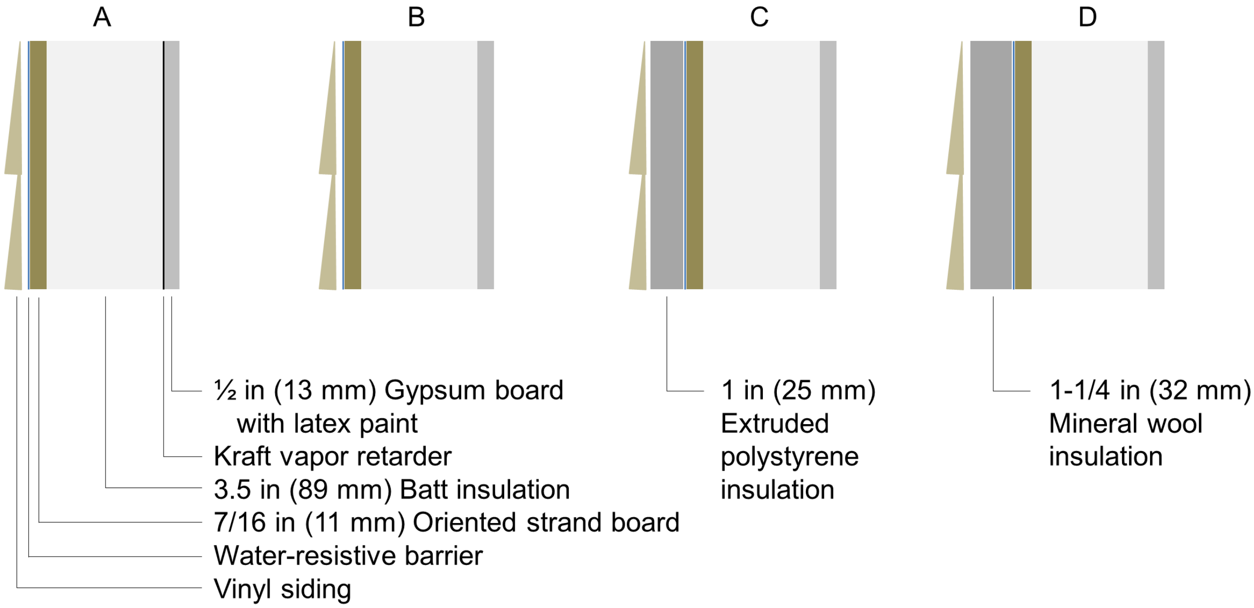

Figure 1. Example Wood-Frame Wall Assemblies.

this moisture or to prevent this moisture from accumulating in the materials through proper storage and protection from rain and flooding during construction. If such measures are included in the design and construction plans, the initial conditions to be used are the equilibrium moisture content (EMC) of each material at 80% relative humidity (RH). The prescribed design initial moisture content of concrete is EMC at 90% RH if specific care is taken to limit initial moisture conditions. If no such measures are planned, the design moisture contents are doubled.

Indoor Environment

Interior conditions include temperature and humidity. The choice of these conditions is extremely important, especially for design analysis of buildings in cold climates. The indoor conditions in buildings and in different zones within buildings can vary considerably; for example, a warehouse will have much different conditions from a swimming pool or shower room. ASHRAE Standard 160 encourages designers to use their own design parameter values if the values are known and part of the design, or if values are prescribed by code, regulation or law, to

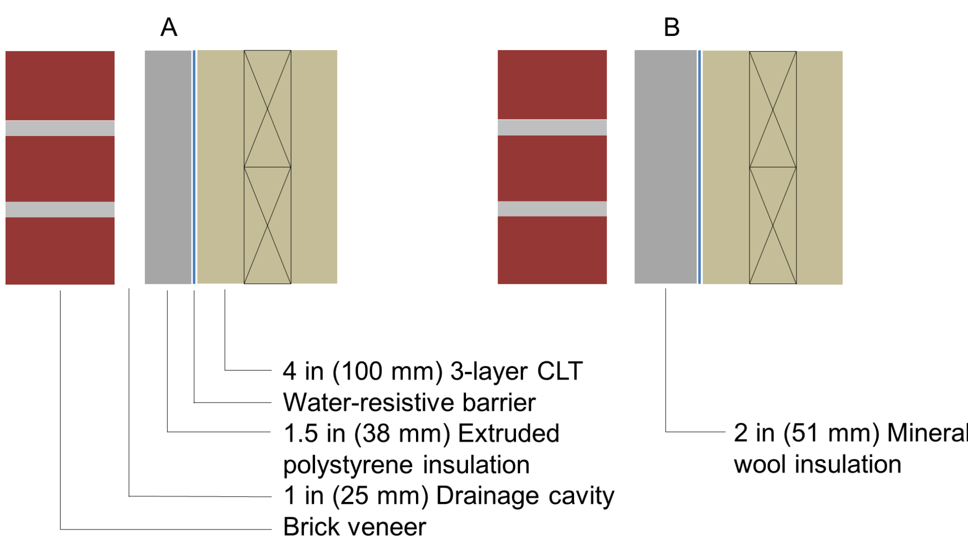

Figure 2. Example Cross-Laminated Timber (CLT) Wall Assemblies.

use those values. If indoor conditions are unknown or not included in the design, the standard provides a simplified procedure or default values. In residential buildings, indoor humidity is rarely explicitly controlled, and default design assumptions are usually needed for these buildings. The standard includes three different methods for determining indoor humidity conditions: simplified method, intermediate method, and full parametric calculation. The reliability of the intermediate method was recently improved with Addendum b to the standard, which is based on analysis of measured indoor humidity and ventilation data. In addition to ASHRAE Standard 160, several European and International standards provide methods for determining indoor conditions (e.g., ISO 2001, DIN 2007). Judgment is needed to select conditions appropriate for the particular building use or occupancy and the particular climate.

Outdoor Environment

Exterior conditions include loads from wind, rain, temperature, humidity, and solar radiation. Severity of conditions can vary considerably from year to year. ASHRAE Standard 160 requires the use of 10 consecutive years of weather data or the use of “Moisture Design Reference Years” (MDRY) to ensure that the analysis is done with appropriately severe weather conditions. In the current standard MDRYs are defined as the 10th-percentile warmest and 10th-percentile coldest years from a 30-year weather analysis (based on mean annual temperature). The standard includes simple formulas for design rain loads on walls for those users who are not inclined, or capable to perform a full wind-driven rain analysis. The standard assumes that some amount of this rain water will penetrate behind the cladding even when adequate flashing is included in the design. The reason is that claddings are usually not completely water tight, especially around windows, doors, and other penetrations. In the absence of specific full-scale test methods and data, the default penetration rate is 1% of the rain deposited on the cladding. The default deposition site for this water is the exterior side of the water-resistive barrier (WRB). If no WRB is present, the designer needs to specify where the water is deposited.

Performance Criteria

Performance criteria are needed to evaluate the results from the design analysis. A detailed overview of failure criteria for building materials is given by Viitanen and Salonvaara (2001). Potential concerns relevant to wood-based structural systems are wood decay, mold growth, corrosion of metal fasteners (see the article by Zelinka in this issue of Wood Design Focus), expansion/contraction damage, and loss of structural capacity. ASHRAE Standard 160 focuses on surface mold growth criteria because under most circumstances these criteria are likely to be the most stringent of all performance criteria (wood decay and structural damage require higher moisture levels and longer duration than mold growth). The standard (as updated in Addendum a) specifies that surface relative humidity on a 30-day running average basis shall be less than 80% when the 30-day running average surface temperature is between 5°C (41°F) and 40°C (104°F). This criterion is thought to be overly simplistic and too restrictive for many cases, and the Standard 160 committee is considering replacing this criterion with a detailed transient mold growth model.

Comparative Hygrothermal Analysis

An alternative to use of performance criteria is to draw comparisons between different variations on a given assembly. Rather than using pass/fail criteria, this approach looks at relative performance between assemblies based on certain metrics. There can be many uncertainties in model inputs, particularly in material properties and boundary conditions, as discussed above. This means that there is generally a higher level of confidence that the simulations will accurately predict relative performance of different assemblies than that the simulations will accurately predict the absolute performance of any given assembly. However, the clear disadvantage is that even the better performing assemblies may still be unsuitable for the climate and interior conditions, and a judgment is still needed. But this can be addressed by including a design that is known to perform well under those conditions. Comparative analysis could involve evaluating assemblies that differ in terms of type of insulation, placement of insulation, or type of vapor retarder, for instance. Analysis could also assess the sensitivity of assemblies to variation in material property values, variation in boundary conditions such as indoor humidity or wind-driven rain, and inclusion of moisture transfer mechanisms such as air leakage. Further examples of this approach can be found in Straube and Smegal (2009), Finch et al. (2013), and Glass (2013).

Simulation Examples

To show the usefulness of hygrothermal analysis in the design of wood buildings, we provide two brief examples and in each case compare the performance of different wall assemblies.

Wood-Frame Construction

This example looks at the drying performance and seasonal trends for oriented strand board (OSB) sheathing in each of the wood-frame wall assemblies shown in Figure 1. The effects of wind-driven rain intrusion and air leakage are not included, both of which significantly change the results. Simulations are started on October 1 at a moisture content of roughly 25% and run for a three-year period. The walls are oriented north and use a climate file from Baltimore, Maryland. Note that the water-resistive barrier is highly vapor permeable.

Figure 3 shows the simulated OSB moisture content for all four walls. The simulations illustrate the effects of an interior vapor retarder and different types of exterior insulation. The baseline wall (A) has a kraft vapor retarder and no exterior insulation. The OSB dries readily and has a repeating annual cycle of lower moisture content in summer and slightly higher moisture content in winter. Wall B omits the kraft vapor retarder (interior latex paint functions as a Class III vapor retarder). This wall dries at approximately the same rate initially, but then accumulates moisture during winter because water vapor migrates more readily through the wall cavity into the OSB from the interior. Wall C adds extruded polystyrene (XPS) insulation between the siding and WRB. Here the OSB dries more slowly because XPS has a low vapor permeance. However, the peak OSB moisture content in subsequent winters is lower than in Wall B because the XPS keeps the OSB warmer (and therefore less prone to moisture accumulation). Wall D changes the XPS exterior insulation to rigid mineral wool exterior insulation. In this wall the OSB dries much faster because mineral wool is highly vapor permeable. During winter the OSB moisture content in Wall D is less than in Wall C because the permeable mineral wool allows water vapor to pass through the OSB to the exterior at a higher rate than XPS.

In summary, this example shows the importance of including an interior vapor retarder (kraft paper) when exterior insulation is not present (assuming no air leakage), and shows that highly permeable exterior insulation allows faster drying than exterior insulation with low vapor permeance. Further details of the simulations, particularly the model inputs with reference to ASHRAE Standard 160 and simulated response of various wall assemblies to wind-driven rain intrusion and to air leakage, can be found in Glass (2013).

Cross-Laminated Timber (CLT) Construction

This example looks at the seasonal performance of the CLT wall assemblies shown in Figure 2, with particular focus on the potential for solar-driven inward diffusion from brick veneer, which is a moisture reservoir cladding. The simulations use a climate file from Houston, Texas. Walls are oriented southeast, which is the predominant direction for wind-driven rain for this weather file. Although rain absorption by the brick veneer is included, intrusion of rain past the cladding is not. The drainage cavity is modeled with an air exchange rate of 2 air changes per hour. Air leakage through the assembly is not modeled. Simulations are started on October 1 at a moisture content in equilibrium with 80% RH and run for a three-year period.

Figure 4 shows the simulated wood moisture content for two CLT wall assemblies. The wood MC for the outermost ½ in (13 mm) of CLT is selected because this location is most sensitive to high exterior humidity conditions. The wall with XPS exterior insulation shows almost no seasonal trend and a very slight drying over three years. The wall with exterior mineral wool insulation accumulates moisture during summer and fall and dries during winter and spring. The climate file happens to have most of the rain occurring in summer and fall. During these seasons, rain wets the brick veneer and moisture migrates inward through the vapor permeable mineral wool insulation into the CLT. Further information regarding the effects of cladding, type of exterior insulation, and climate for CLT wall assemblies can be found in Chapter 10 of the U.S. CLT Handbook (Glass et al. 2013).

Concluding Remarks

This article emphasizes the importance of considering moisture performance during the design process and presents a brief introduction to computer-based hygrothermal simulation as a tool for building envelope design analysis. As with any simulations, the results are only as good as the provided inputs; hygrothermal simulations are sensitive to indoor and outdoor conditions as well as material properties. ASHRAE Standard 160, *Criteria for Moisture-Control Design Analysis in Buildings*, addresses the need for standardized moisture design loads and performance criteria. Comparative hygrothermal analysis can be useful for predicting the relative performance of different building assemblies or investigating sensitivity to certain model inputs. Simulations of light-frame and cross-laminated timber wall assemblies included here illustrate the usefulness of hygrothermal analysis in the design of wood buildings.

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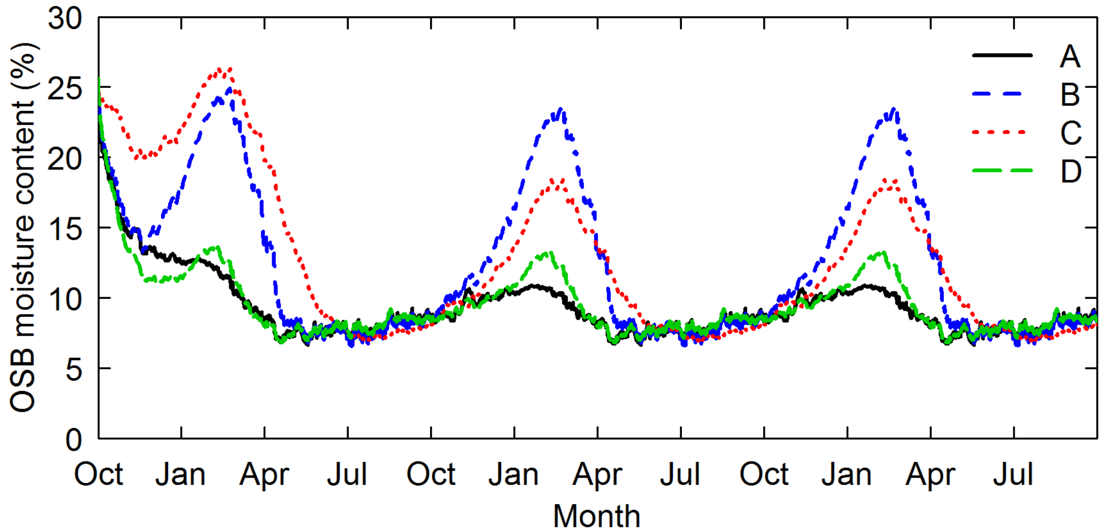

Figure 3. Simulated Moisture Content in OSB Sheathing over Three Years for Wall Assemblies A (Kraft Vapor Retarder, No Exterior Insulation), B (No Kraft, No Exterior Insulation), C (No Kraft, Extruded Polystyrene Exterior Insulation), and D (No Kraft, Mineral Wool Exterior Insulation) (see Figure 1). The Walls are North-Facing and Located in Baltimore, Maryland.

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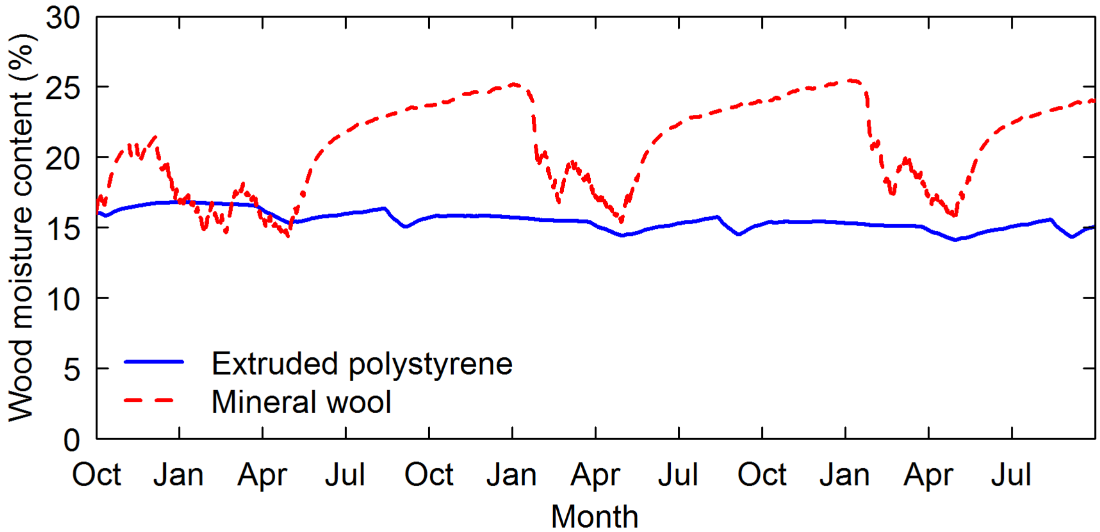

Figure 4. Simulated Moisture Content in the Outermost ½ in (13 mm) of CLT over Three Years for Wall Assemblies with Either Extruded Polystyrene or Mineral Wool Exterior Insulation (see Figure 2). The Walls are Southeast-Facing and Located in Houston, Texas.

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