Effects of Moisture Absorption Mechanisms on In-Service Design R-Values of Polystyrene Insulation*

XPS and EPS Behave Differently in Moist Below-Grade Applications

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ABSTRACT

Moisture uptake in polystyrene insulation may occur via liquid-water capillary action, water vapor diffusion, and liquid-water diffusion. This paper describes the physical differences between XPS and EPS and how these inherent differences affect the moisture uptake mechanisms and moisture absorption. Also presented are challenges of evaluating moisture uptake in XPS and EPS. The paper concludes with suggestions for more accurate predictions of moisture absorption in moist service applications of XPS and EPS insulation. More accurate predictions of in-service moisture absorption will aid decisions regarding design R-values for polystyrene insulation in moist or wet service below-grade applications.

Moisture absorption is a familiar concept. Although moisture absorption mechanisms in polystyrene insulation are easy to understand, some claims about insulation performance can be misleading. Marketing claims are often made based on test results from a few field samples; and, consequently, long-term field performance could be erroneously extrapolated from small scale laboratory tests of limited duration and exposure.

Ideally, engineers and specifiers would have access to peer-reviewed data from known scientific institutions and they could sort through the marketing claims. Furthermore, sophisticated mathematical modeling is emerging to help predict polystyrene insulation performance in a range of climate conditions, but in the meantime, long-term field research studies are the best resource for reliable information.

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All polystyrene insulation products allow water vapor diffusion. Specific to expanded polystyrene (EPS) however, water in liquid or vapor form travels through the network of channels between the fused EPS beads. These fine capillaries are capable of transporting water deeply into the EPS insulation in a very short period of time.

Extruded polystyrene (XPS) insulation and expanded polystyrene (EPS) insulation are both used in applications with high potential for moist or wet service exposure, such as below-grade foundations, slabs, and geofoams, as well as protected membrane roof assemblies (PMRAs). While proper drainage is recommended in all applications, in below-grade cases, insulations may still be exposed to liquid water and water vapor over many years. Likewise, PMRAs may be exposed to intermittent water over wet seasons. XPS and EPS insulations both absorb some moisture from exposure to water for extended periods of time; however, research—from the 1970s to the present day—has consistently shown that XPS absorbs significantly less moisture than EPS with the differences becoming most apparent after about six years.[1-2]

Cai *et al.* systematically collected and analyzed published field and laboratory data on moisture absorption of XPS and EPS.[1] Moisture absorption dramatically affects the thermal performance of these two similar-yet-different insulations. Understanding, and potentially predicting, moisture absorption in XPS and EPS in moist or wet service applications is important because long-term moisture exposure typically results in a reduction of in-service R-value. And, this reduction in R-value is directly correlated to the amount of moisture absorbed.[2-5]

Moisture uptake is the increase in water content of a material, typically reported as volume percentage or a weight percentage. Moisture uptake in polystyrene insulation may occur via liquid-water capillary action, water vapor diffusion, and liquid-water diffusion. This paper describes the physical differences between XPS and EPS and how these inherent differences affect the moisture uptake mechanisms and moisture absorption. Also presented are challenges of evaluating moisture uptake in XPS and EPS. The paper concludes with suggestions for more accurate predictions of moisture absorption in moist service applications of XPS and EPS insulation. More accurate predictions of in-service moisture absorption will aid decisions regarding design R-values for polystyrene insulation in moist or wet service below-grade applications.

Understanding Moisture Movement

For moisture to move into and through polystyrene insulation, a driving force and a pathway to travel are required. The driving force could be a greater pressure of liquid water on one side of the insulation than the other, or a greater pressure of water vapor on one side than the other. The greater the pressure difference, the greater the driving force for moisture to travel through the insulation

Driving force + Pathway = Transport

Moisture uptake is dictated by the properties of the materials. Just as polystyrene insulation microstructure affects heat transfer so, too, it affects moisture transport. This relationship between microstructure and moisture uptake especially holds true for insulation materials, which may absorb moisture through multiple mechanisms. The moisture uptake potential of an insulation material, therefore, is an important property to consider when designing with XPS or EPS (Fig. 1).

Characteristically, specifically to EPS, water in liquid or vapor form can and does travel through the network of channels between the fused EPS beads. Capillary transport of liquid water is much faster than vapor diffusion through the closed cell foam structure. Large amounts of liquid water can be transported through the interstitial channel network with little restriction within seconds. Hence, capillary action can accomplish in seconds what takes years by vapor diffusion.

Although capillary action is limited to the volume of the channel network, water from the interstitial channel network also contributes to diffusion of water into the body of the beads. Additionally, the water trapped in the channel network conducts heat very well (25 times more efficiently than the foam), thereby bypassing the insulation and reducing the effective R-value of the EPS insulation.

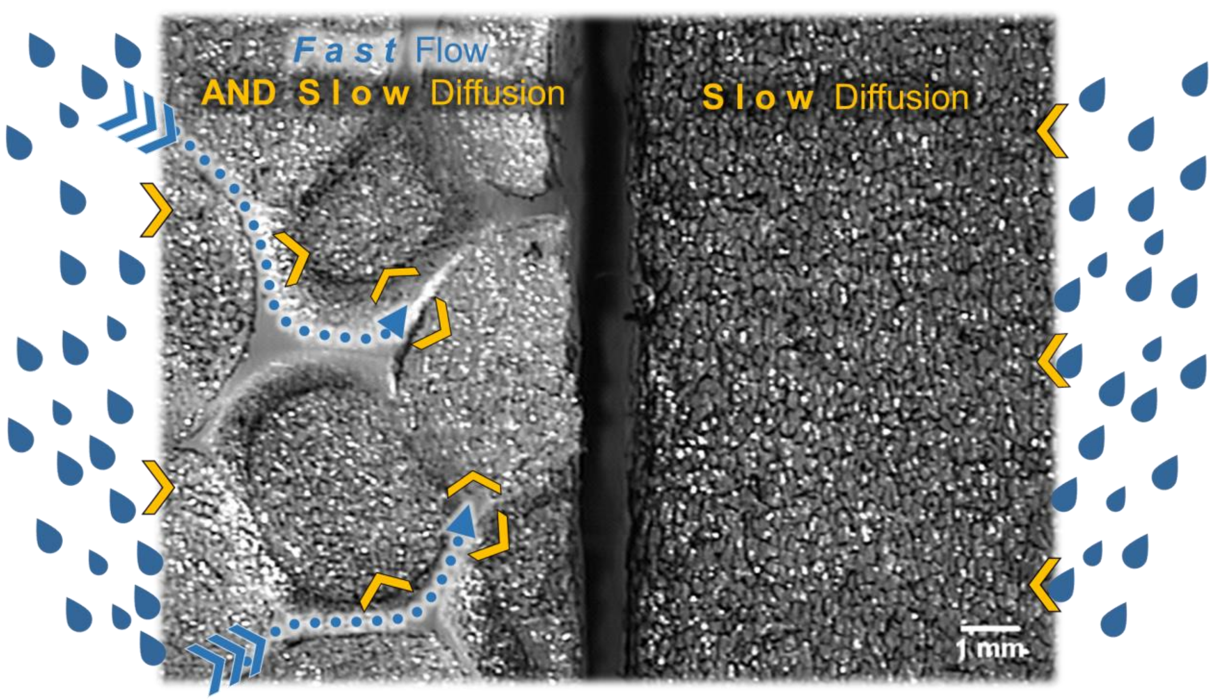

Figure 1 — Micrograph of side-by-side EPS (Type XIV, left) and XPS (Type IV, right) foam specimens. A continuous mass of closed foam cells is seen on the right. Interstitial channels are evident on the left. The cut surface of both foam specimens highlighted using black ink to enhance imaging contrast; areas not coated with ink are out of the cut surface plane. Incident moisture transport paths are depicted as droplets and arrows.

Moisture sources include water vapor in the air or soil surrounding the insulation and liquid water in direct contact with the insulation surfaces. Constant exposure to water leads to absorption of water in the polystyrene insulation and results in a proportional reduction in thermal resistivity (R-value) as measured on samples extracted from below-grade applications.[2, 3, 6-8] In the case of continuous exposure to below-grade liquid moisture, the insulation may be further compromised by contaminants in the soil and repeated cycles of freezing and thawing.[9-12] Adjustments to design R-values are required to account for long-term moisture absorption in the real world.[4] It is critical to understand the effects of continuous exposure to water on the thermal performance of polystyrene insulations in various below-grade applications.[6-8]

Understanding moisture transport mechanisms in polystyrene foams allows material specifiers to select materials wisely for service in wet applications.

The Problem with Using Short-Term Testing to Characterize Long-Term Performance

Predicting in-service moisture absorption in polystyrene insulation and its effect on thermal resistance is a challenging issue because the material standard, ASTM C578, *Standard Specification for Rigid, Cellular Polystyrene Thermal Insulation*,[5] does not address in-service moisture absorption. Manufacturers of polystyrene insulation are in concordance that small-scale, short-term testing—for example, as prescribed by ASTM C272, *Standard Test Method for Water Absorption of Core Materials for Sandwich Constructions*,[13] or as required per ASTM C578—is not a predictor of long-term in-service moisture absorption, and therefore not a predictor of the long-term in-service effects on R-value performance in wet environments.

A bulletin from the EPS Industry Association makes the following statements[14]:

> This testing further confirms that water absorption results determined using ASTM C272 "Standard Test Method for Water Absorption of Core Materials for Structural Sandwich Materials" cannot be correlated to the in-service performance of foam insulation.
>
> […]
>
> In fact, laboratory test methods were not developed for predicting actual performance, but were intended for use in specifications as a means of comparing relative physical properties of different cellular plastics and for product evaluations and quality control.

The source of misinterpretation of test results is not the testing. Short-term testing is intended to maintain a consistent manufacturing practice, but misuse of the test results only complicates and obfuscates the long-term prediction of moisture performance. Short-term testing complicates the larger challenge because the results of short-term testing can be misleading. The basic problem of interpreting moisture absorption performance has to do with how XPS and EPS are made and the consequences of the different manufacturing processes on XPS and EPS materials properties and moisture absorption.

The EPS manufacturing process results in voids between the beads in the material, which leave the material vulnerable to rapid moisture uptake. By contrast, XPS manufacturing results in a continuous foam board without interconnected voids. The physical mechanisms driving moisture movement and moisture uptake in EPS and XPS are outlined in the next three sections, leading to data-backed claims later in this paper.

Capillary Action as a Primary Mechanism

To reiterate: The main structural difference between XPS and EPS is the presence of a network of interstitial voids between the closed-cell foam beads in EPS. Think of them as capillary tunnels going everywhere throughout the EPS insulation material. Despite hydrophobicity of polystyrene, liquid water can move through these voids due to capillary action. Because the microstructure of XPS has no interconnected voids, little or no liquid water transport occurs by capillary action within XPS. See sidebar for more about capillary action.

Manufacturers may employ various surface modifications to EPS insulation to inhibit moisture absorption. For example, some EPS is manufactured with product facers, which reduce moisture absorption in short-term laboratory tests. Despite the presence of facers, moisture is absorbed into the EPS through capillaries exposed at the unprotected edges of the EPS, and through punctures in the facers (Fig. 2).

Vapor Diffusion as a Secondary Mechanism

The mechanism of water vapor diffusion into and out of the cellular structure occurs within polystyrene insulation at a much slower rate than capillary action.

In closed-cell foam (that is, the individual insulation beads of EPS; or the entire insulation board for XPS), water molecules may diffuse through the polystyrene foam cell walls and through the gas inside the foam cells. The diffusion process is slow at ambient conditions; it could take years to infiltrate a closed-cell foam structure with even one percent (by volume) of water via diffusion, and it takes a similarly long time to drive moisture out by diffusion. The rate of wetting or drying by diffusion depends on the moisture content in the surrounding environment.

Regarding liquid water transport, no liquid water can flow through the closed cell structure of polystyrene insulation. Moisture intrusion in XPS occurs *only* by the slow process of water *vapor* diffusion through the matrix of closed cells. Capillary action is absent in XPS other than a minor effect of liquid water accumulating on cut edges introduced during manufacturing but not moving through the insulation.

Figure 2 — A Stone Slinger "throw conveyer" throws aggregate through the air at a construction site. Stone Slinger is a trademark of W.K. Dahms Mfg. Ltd. (Photograph used with permission. For more information, www.stoneslinger.com)

Water vapor diffusion occurs in both EPS and XPS but is much more pronounced in EPS because water vapor diffusion is facilitated by the previously described capillary action: Moisture transmission through the voids between the beads allows moisture to quickly penetrate deep into the EPS insulation and subsequently there's more surface area for vapor diffusion and higher water content compared to XPS.

The Role of Drying

If polystyrene insulation is primarily in a damp or wet environment, then effective drying is highly unlikely. Extensive evidence compiled by Cai *et al.* supports this.[1, 4] The drying of polystyrene insulation in most below-grade applications is uncommon; rather, moisture content in insulation increases with years in-service.

Arguments have been advanced that R-values are restored when "wet" insulations are dried out. It has been claimed that materials that are fast to absorb water are also fast to dry out. It has been claimed that, even if EPS absorbs many times its own weight in water, the water can be drained, the EPS can be dried out, and the thermal performance can be restored to its initial value as if nothing happened. This argument is often used to excuse or rationalize the high moisture absorption of EPS compared to XPS. According to this line of thought, EPS relies on the surrounding substrate to develop a drying potential that counters the rapid uptake of moisture, whereas XPS relies on blocking moisture uptake from the beginning as part of a properly designed system. The speciousness of the argument is echoed by the lack of evidence that wet service applications create a drying condition for an extended period of time beyond a seasonal drying period followed by an equivalent wetting period. The basic question remains:

> *Does the drying period of the surrounding substrate exceed the wetting period, thus effectively negating moisture uptake, in either EPS or XPS?*

If the EPS or XPS insulation is primarily in a wet environment, then effective drying is highly unlikely. Extensive evidence compiled by Cai *et al.* suggests that is the case.[1,4] Drying in the field is uncommon; rather, in most below grade cases, moisture content in insulation increases from year to year. Further evidence that insulation drying is unreliable is observed in commercial roofing applications that use EPS insulation. Water-soaked EPS insulation is often a factor in the failure of roofing systems *even when the roofing systems are designed to drain and avoid ponding*.[15] Above-ground roofing applications with drainage sometimes fail to dry, possibly due to overwhelming the system with an unexpected event or a blockage in some part of the drainage system; hence, EPS insulation is even less likely to dry in water contact applications where drainage is more complex (Fig. 3).

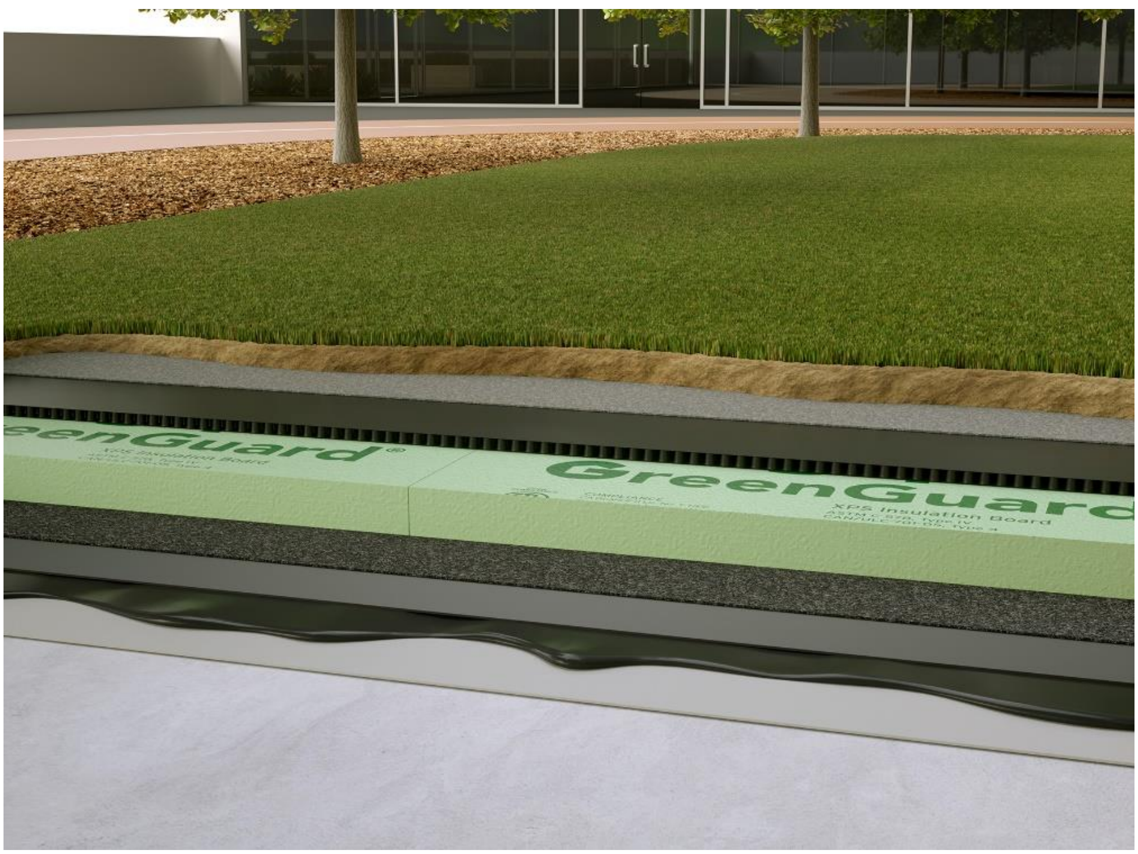

Figure 3 — Protected Membrane Roof Assembly (PMRA) with green roof features. Photograph Courtesy of Kingspan.

Evaluating Moisture Uptake in XPS and EPS

Once moisture absorption takes place, long-term data suggest that the water remains in polystyrene foam insulations in moist or wet below-grade applications. Although small-scale testing indicates the potential for drainage and drying, drainage and drying of XPS or EPS in moist or wet below-grade is not confirmed by long-term field studies.

Short-term exposure laboratory tests are inadequate to characterize in-service moisture content for the following reasons:

1) The long-term effects of exposure to water are not well represented by short-term laboratory tests as prescribed by ASTM test method C272[13] because 24 hours of water immersion, per ASTM C272, is not enough time to fully replicate the mechanisms that lead to both long-term liquid and vapor moisture uptake in polystyrene insulation.

2) In-service, the wetting cycle may exceed the drying cycle and gradually increase moisture absorption over time as shown by the Connor data.[6] This wet/dry hysteresis of in-service insulation is not fully replicated through short-term exposure testing using an extreme laboratory wet/dry cycle. The claim that EPS will "dry" itself in-service after being exposed for lengthy periods of liquid moisture immersion does not stand up to scrutiny. Claims often are based on a faulty premise that polystyrene placed next to moisture absorbing soils will be dry more often than wet.

3) Conditions that promote drying are exceedingly rare in typical below grade applications as has been amply demonstrated by Connor.[6] Connor and his predecessors measured water content and other physical properties of samples extracted from below-grade applications after years and decades in service in locations spanning climate zones 4 through 8.[2, 6-8, 16-18] Figure 6 summarizes this data and plots measured water content (by percent of volume) and retained R-values per inch of polystyrene foams. It indicates the extent of differences of moisture accumulation in polystyrene foams after up to 30 years in service. Other peer-reviewed data show that wetting below grade is significant and drying is limited.[1, 4]

4) Manufacturers have been known to produce EPS insulations with a skin, or facer, on the surface. Product facers can slow moisture absorption enough to pass laboratory tests but facers may not demonstrate long-term durability; as the facer deteriorates or is damaged, the EPS may then be subject to capillary action, rapid moisture uptake and subsequent reductions in R-value performance. These facer materials may mimic the behavior of denser XPS by reducing the number of voids near the surface, thereby inhibiting moisture uptake by capillary action in the first few millimeters of the insulation. That may lower the moisture absorption in short-term, small-scale testing. However, in below grade applications constantly exposed to water, moisture absorption takes place in the insulation despite this protective skin. [1, 4]

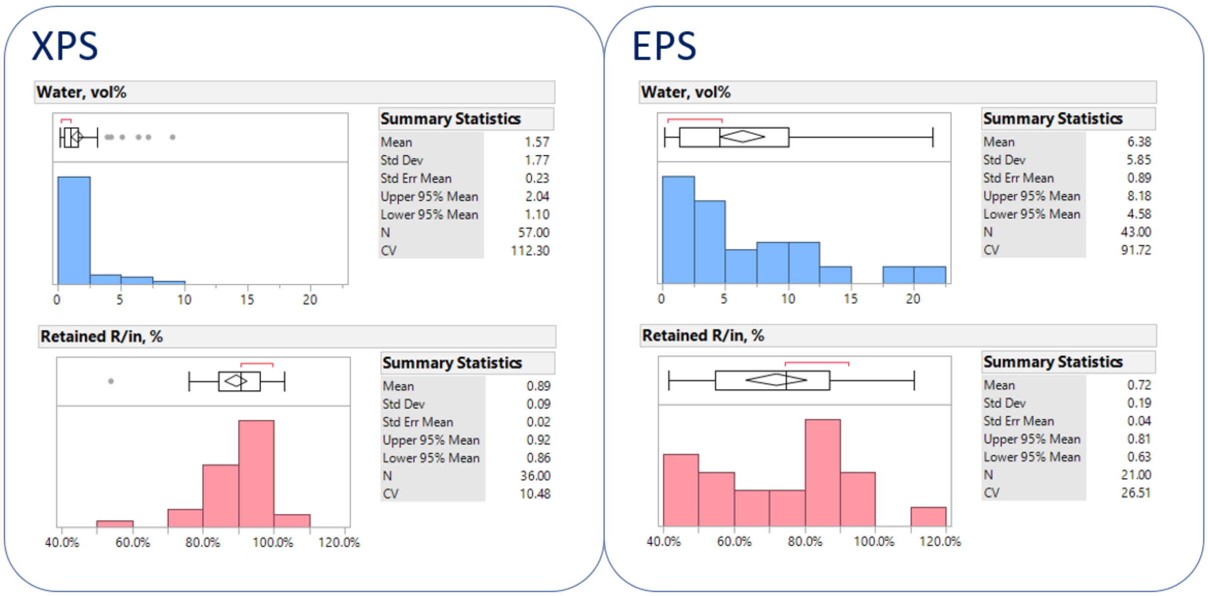

Figure 4 — Statistical analysis of water absorption (percent by volume) and retained R-value per inch, for XPS (left side) and EPS (right side).

Research suggests that retained R-values after subjecting to extreme wetting and drying in short-term testing do not represent actual R-values in real-world, in-service conditions.[1, 4, 6] One such claim is the use of ASTM C1512, *Standard Test Method for Characterizing the Effect of Exposure to Environmental Cycling on Thermal Performance of Insulation Products*, to look at the retained R-value after the effects of wetting and drying cycles.[10] The wetting and drying prescribed by ASTM C1512 is a very limited exposure of 28 days to water vapor. The data studies by Cai *et al.*[1, 4] and Connor[6] examine years and decades of exposure (thousands of days; not one cycle of 28 days).

So, what is the best method to predict the R-value of insulation in-service?

Going forward, what should designers anticipate for future research?

Toward Accurate Prediction and Modeling

There are two complementary paths forward, allowing for the prediction of in-service design R-values for moist or wet service applications of XPS.

The first path involves paying greater attention to long-term field tests.[6] Moisture content and R-values should be measured on the samples as they are found. This is the practice used by Connor[6] and his predecessors.[7, 8] Actual in-field moisture data and R-values are much more meaningful to specifiers as well as much more useful in developing simulations and models for moisture absorption.

The results of long-term field tests support, for example, the XPS and EPS design values that are recommended in ASCE 32 for frost-protected shallow foundations (FPSFs).[11-12] Design values in ASCE 32 may be used for below-grade applications with exposure similar to FPSFs. If anything, the moisture data from long-term field tests suggests the design values for EPS in ASCE 32 may need to be revised to be more conservative.[16, 17]

Orientation is also a consideration. Insulation can be installed vertically or horizontally, which has consequences regarding moisture absorption depending on application. The differences in design values for vertical applications versus horizontal applications have been studied extensively and are addressed within ASCE 32 as applied to frost-protected shallow foundations.

The second path involves modeling of the behavior of insulation types. It should be possible to input the type of insulation into a model along with estimates of seasonal temperature and moisture conditions. The output of the model would be predictions of moisture content and R-values versus time. The models would also include estimates of the margins for error according to a database of real-world data.

Complex moisture movement through the cellular structure of the foam insulation can be modeled using hygrothermal modeling software. One of the better known hygrothermal modeling environments accounting for moisture uptake of materials is WUFI®,[19] but other hygrothermal modeling software packages also exist.[20] Note that generic material characteristics pre-set in such software packages may not accurately account for material-specific impacts of absorbed moisture.

Some of the models specific to impact of moisture accumulation in polystyrene insulation have already been developed, and their predictive power continues to grow.[20, 21] For example, Cai *et al.*[19] developed a multi-scale model to study the hygrothermal performance and impact factors of closed-cell thermal insulation from first principles, and it shows good agreement with experimentally observed data. In another development, Woodcraft *et al.*[22] use a fundamentally-derived thermal conductivity model, accounting for moisture impact, to fit data from field studies and laboratory experiments where insulating foams were subjected to moisture in various forms. Incorporating models of moisture impact on hygrothermal behavior of materials improves accuracy of such model predictions.

Summary

While moisture impact models are making their way into the hygrothermal modeling and becoming commonplace, use of ASCE-32 long-term design R-values in moisture-contact applications still are recommended.

For the present, there will likely be little agreement on standards for testing the long-term performance of polystyrene insulations, although laboratory work and modeling will continue in the interest of developing improved materials for specific applications.

Until such time that predictive models are accepted for use, where long-term thermal performance of XPS or EPS foam insulation in moist below grade applications is a priority, designers would be advised to consider the long-term moisture absorption dynamics of XPS and EPS, and to consider the effects on long-term thermal performance (retained R-value) of XPS and EPS, and the relative thickness required in these applications.

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