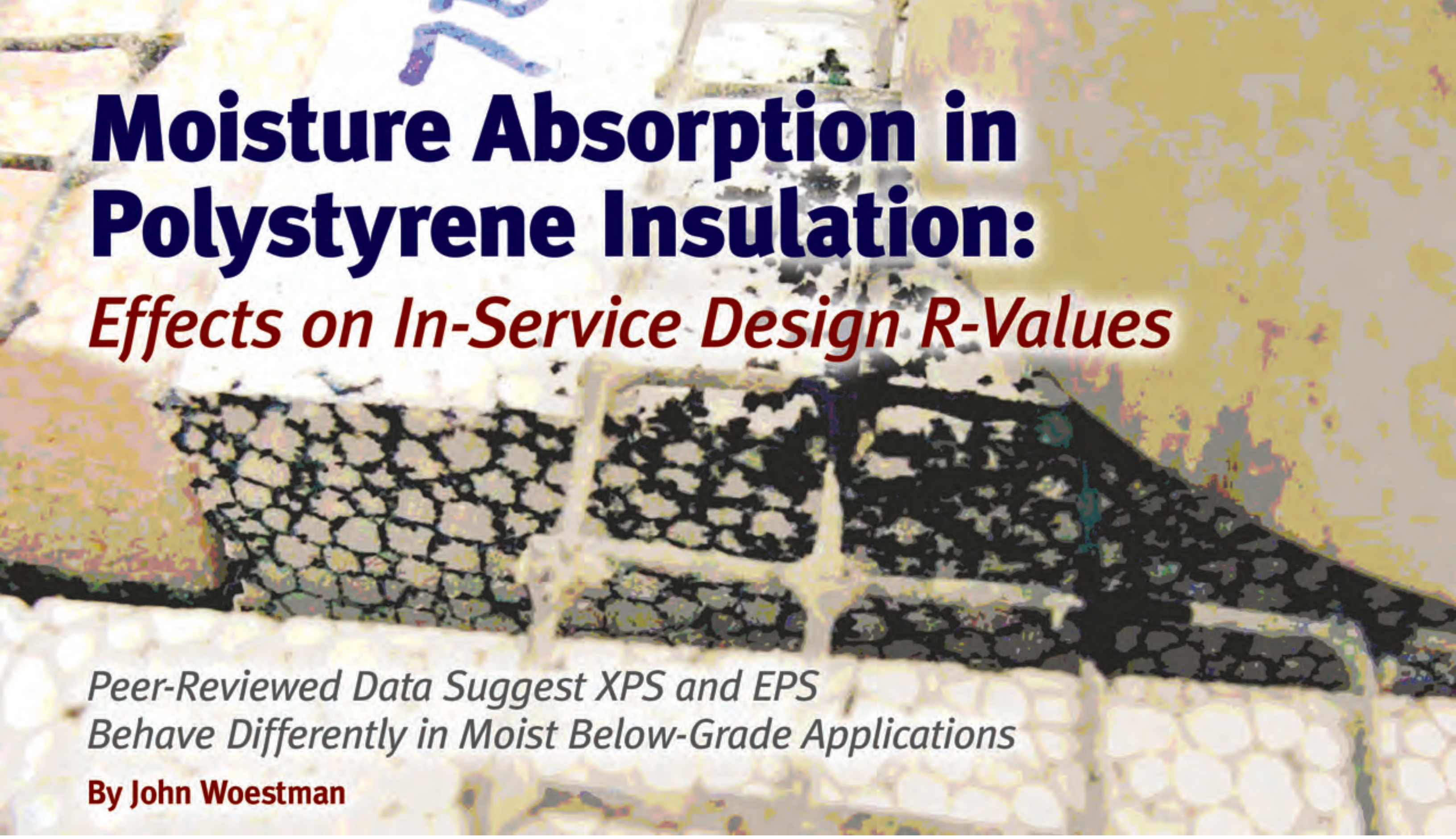


Moisture Absorption in Polystyrene Insulation:

Effects on In-Service Design R-Values

Peer-Reviewed Data Suggest XPS and EPS Behave Differently in Moist Below-Grade Applications

By John Woestman

Moisture absorption is a familiar concept. It is easy to understand moisture absorption mechanisms in polystyrene insulation. Unfortunately, some insulation-performance claims can be misleading when based on test results from a few field samples or extrapolations of long-term field performance 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 to sort through the marketing claims. 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.

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. The channels are very small; in fact, they can be considered capillaries. This process of capillary transport of liquid water is much faster than that of vapor diffusion through the closed-cell foam structure. Liquid water can be transported through the interstitial channel network with little restriction within minutes.

Extruded polystyrene (XPS) insulation and 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 shown that XPS typically 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 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. 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 a 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

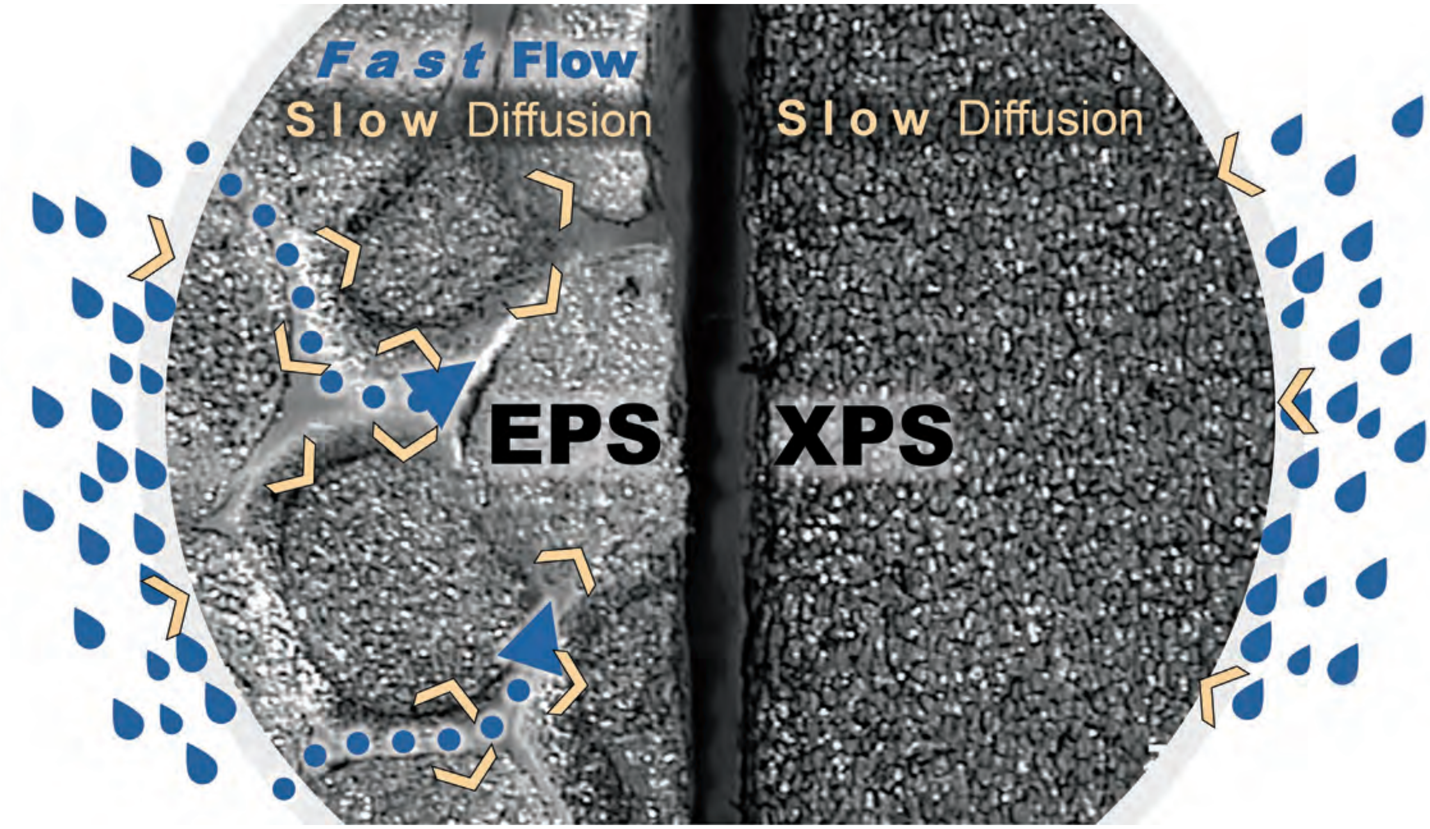


Figure 1 – Micrograph of side-by-side EPS (Type XIV, left) and XPS (Type IV, right) foam specimens. A continuous mass of closed-foam cells is seen on the right. Interstitial channels are evident on the left. The cut surface of both foam specimens is highlighted using black ink to enhance imaging contrast;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

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, it also 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 insulation (*Figure 1*).

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 it is not a predictor of the long-term in-service effects on R-value performance in wet environments. A brief review of moisture absorption mechanisms will outline the physics that drive the movement of moisture to support data-driven claims.

KEY MECHANISMS OF MOISTURE ABSORPTION

Capillary Action

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. 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.

Vapor Diffusion

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*).

The Trouble With Presumed Drying

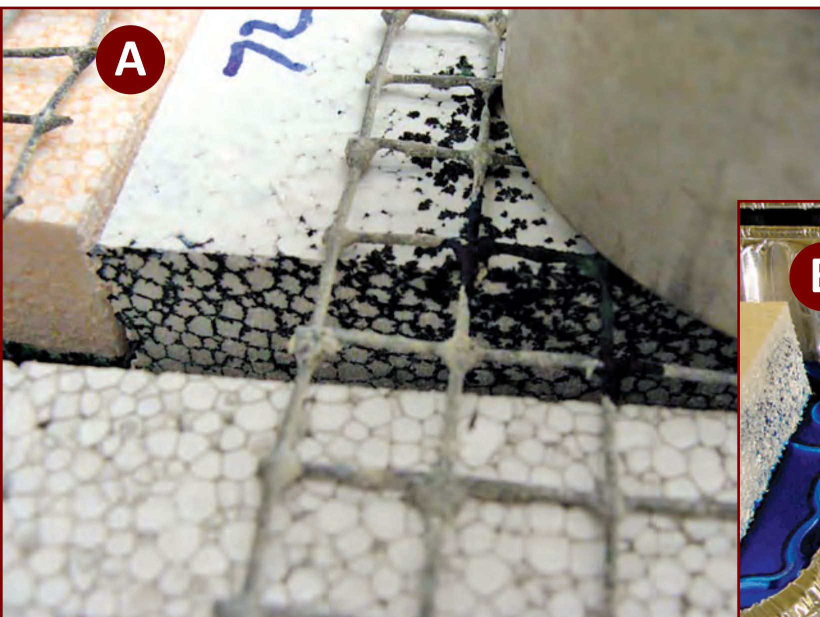
If polystyrene insulation is primarily in a damp or wet environment, then effective drying is highly unlikely. Extensive evidence compiled by Cai et al. supports this.[1,4] Drying of polystyrene insulation in most below-grade applications is uncommon; rather, moisture content in insulation increases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

CHALLENGES OF 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 applications 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.



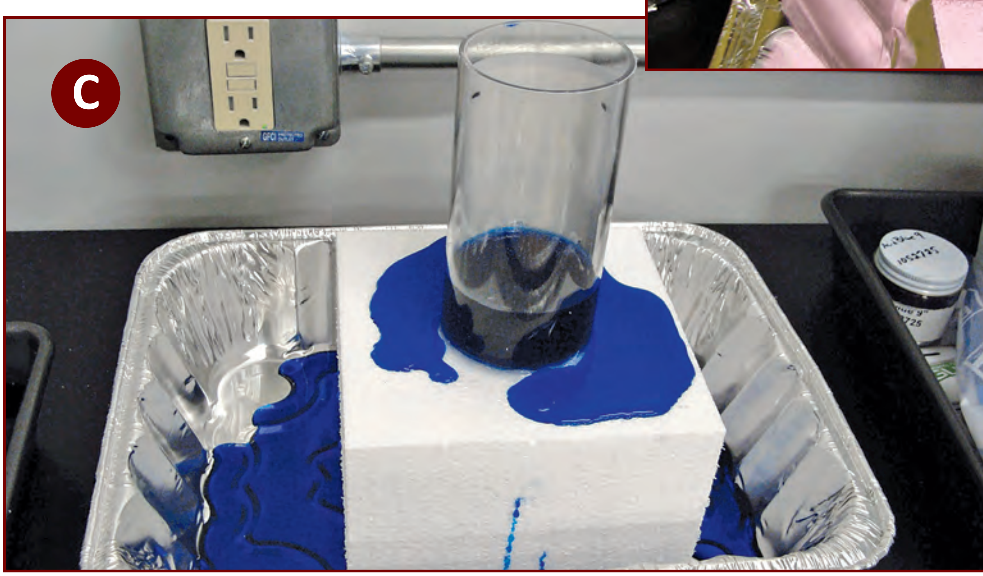


Figure 2 – (A) EPS capillary uptake of water with water-soluble dye from lower to upper surface follows voids between EPS beads. (B) No leakage is observed in the XPS due to hydrostatic pressure and capillary action. (C) Leakage is observed in the EPS due to capillary action under hydrostatic pressure. Photographs courtesy of Owens Corning.

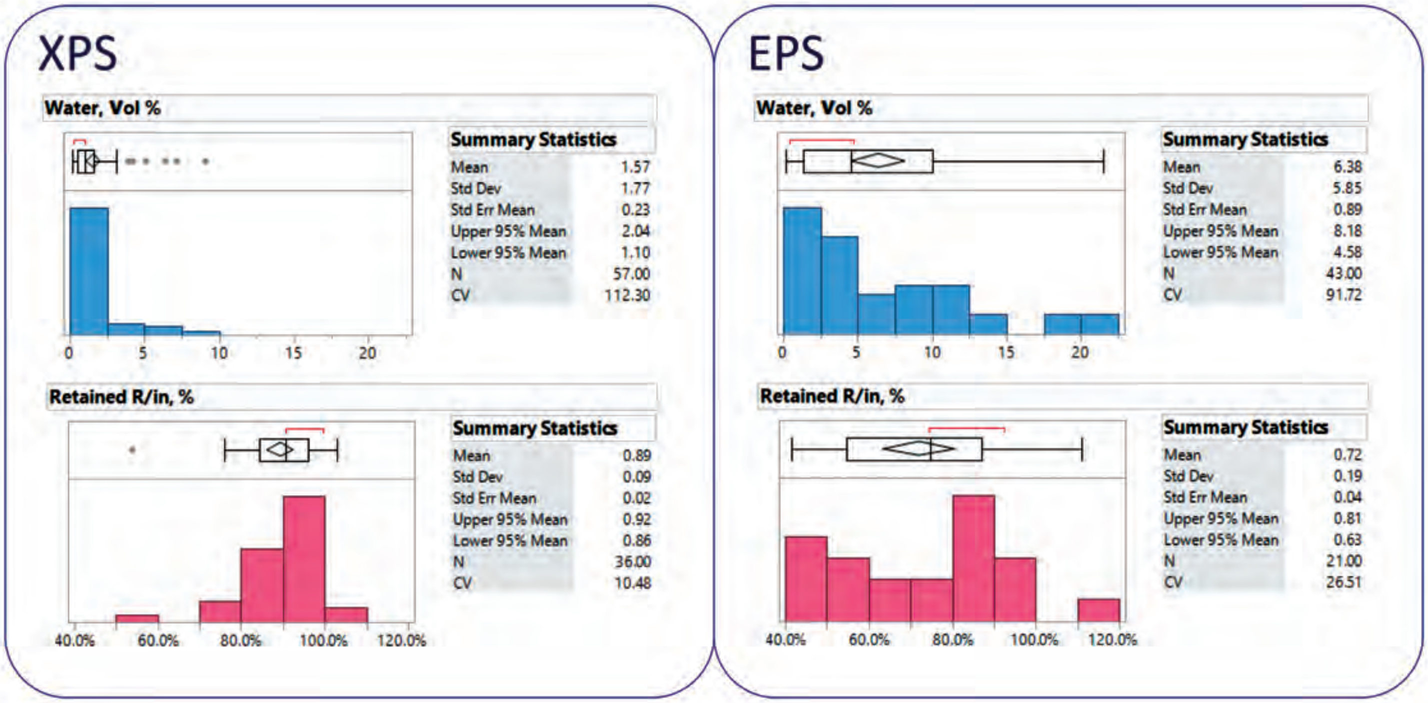


Figure 3 – Statistical analysis of water absorption (percent by volume) and retained R-value per inch, for XPS (left side) and EPS (right side). Figures courtesy of Dupont.

2) In service, the natural wetting cycles may exceed drying cycles and gradually increase moisture absorption over time. This wet/dry hysteresis of in-service insulation is not fully replicated through short-term exposure testing using an extreme laboratory wet/dry cycle.
3) 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.[2,6-8,14-16] *Figure 3* summarizes these 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]

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, rather than 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 and are 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.

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®,[17] but other hygrothermal modeling software packages also exist.[18] 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.[19,20] For example, Cai et al.[19] developed a multiscale 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.[20] 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 is still 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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ORNL and FEMP Build Smart Walls

The EMPOWER "smart" wall has internal tubes for storing cool water.

Oak Ridge National Laboratory (ORNL) and the Department of Energy's Federal Emergency Management Program (FEMP) have partnered to create a prototype wall named "EMPOWER." This "smart" wall is 3-D printed using a manufacturing system called SkyBAAM, which prints concrete. SkyBAAM constructs walls without the use of a gantry system, and it reportedly can be set up within hours with minimal preparation.

The wall is embedded with tubes which are pumped full of water from a chiller, lowering the wall's interior temperature. Dynamic insulation uses the coolness stored inside to control the temperature on the outside of the wall. This allows the wall to assist in cooling the room, reducing the need for use of HVAC. The wall also has a dedicated battery to store energy during low-demand hours to be used during peak hours, reducing the load on the grid and decreasing the demand for electricity.

You can view a video about these walls at https://youtu.be/ANPn7c_KEBA.