Demystifying Rigid, Cellular Polystyrene Insulations

Separating Fact from Fiction on Real World Construction Projects

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Figure 1 – RCPS is often installed beneath airfields in cold climates. (Photograph Courtesy of DuPont.)

1. Introduction

Rigid, cellular polystyrene (RCPS) foam boards are used as thermal insulation in assemblies for exterior walls as well as roofs [1], basements [2] and cold climate infrastructure [3]. Considering all these applications (Figs. 1-3). It is remarkable that the number of generic "types" could be reduced to just fourteen according to ASTM C578 "Standard Specification for Rigid, Cellular Polystyrene Thermal Insulation" [4].

This paper addresses the myths surrounding the various types of polystyrene insulation and their applications as well as caveats that should be heeded when specifying insulation thickness based solely on the R-values listed in ASTM C578.

The main purpose of the ASTM standard is to allow products from different manufacturers to be classified according to basic physical properties that can be measured in a laboratory using standardized test methods. It provides guidance for testing physical properties such as compressive resistance, flexural strength, and thermal resistance to ensure continued compliance to the product standard. In an ideal world, specifying manufacturing parameters would be enough. However, foamed polystyrene performance in the real world is all that matters for designers. Hence this paper also examines how physical properties change as insulations interact with the environment.

Figure 2 — RCPS is often installed in below grade applications for habitable basements. (Photograph Courtesy of Kingspan.)

2. Caveats for the End-User

There is no definitive insulation standard such that a designer can lift an R-Value from a table without further consideration of end-use conditions. Designers need deep knowledge of factors affecting the long-term performance of insulations. This knowledge can be gained from science, experience, and *de facto* best practices.

Guidance from individual manufacturers and industry associations is also of value but such information can be limited. “Buyer beware” applies in the marketplace. There is no substitute for a detailed understanding of the long-term and short-term material properties of insulations in specific applications.

These caveats are mentioned in Appendix X1 of the ASTM C578 material classification standard. While this appendix is designated as “Nonmandatory Information,” it includes vital topics such as

X1.3 Water Vapor Transmission
X1.4 Water Absorption
X1.5 Freeze/Thaw Exposure
X1.7 Thermal Resistance Values at Additional Mean Temperatures

For a construction specifier, engineer, or architect, the advice in Appendix X1 may be equally relevant compared to the body of the standard, which gives mandatory testing information for manufacturers. The specifier should keep in mind that R-values are affected by the in-use temperature changes daily and seasonally and by the moisture absorption and outgassing of blowing agents over time periods of years and decades.

On the one hand, extruded polystyrene (XPS) types are subject to long-term aging due to diffusion of blowing agents and air. The heavy molecules of the blowing agent slowly diffuse out and lighter air and water vapor molecules diffuse in. As a result, the R-value typically decreases by a predictable amount of one to two percent over the life of the product, often spanning several decades. This effect can be determined and reported in accordance with ASTM C1303 Test Method for Predicting Long-Term Thermal Resistance of Closed-Cell Foam Insulation [5]; or CAN/ULC S770 Test Method for Predicting Long-Term Thermal Resistance of Closed-Cell Foam Insulation [6]. ASTM C578 requires that LTTR be reported for five types (i.e., IV, V, VI, VII and X). Expanded polystyrene (EPS) typically is not subject to this gas exchange mechanism and associated accelerated testing.

On the other hand, moisture absorption is a more deleterious factor. ASTM C578 prescribes only short-term moisture absorption tests, using narrowly defined laboratory conditions. These can be informative for classification purposes, but it is insufficient for engineering design considerations. This paper discusses various aspects of moisture absorption in polystyrene (EPS and XPS) insulations and the pitfalls of using ASTM C578 R-values in real-world designs.

The purpose of rigid, cellular polystyrene (RCPS) foam boards is to manage the hygrothermal performance of roofs, walls, foundations and cold-climate infrastructure. The thickness and properties of the foam boards controls the location of the dew point temperature within the building envelope elements. Moisture absorption properties are especially important with respect to how moisture is transported through the insulation as well as the condensation of moisture within the bulk of the insulation.

Susceptibility to *long-term* moisture absorption is not quantified in ASTM C578. Informed design controls the environment through the strategic use of the neutral specifications and knowledge of how RCPS foam boards interact with the environment over long periods of time. ASTM C578 currently has no required test method to characterize the long-term effects of exposure to moisture. It is up to the designer to gain profound knowledge about these factors and develop an appropriate defensive strategy.

In other words, the values given in ASTM C578 can be likened to the rules of a game such as basketball or chess. The rules of manufacturing and classifying the various types according to ASTM C578 are not in dispute. Nonetheless, how these specifications are applied has more to do with the talent of the designer in developing a defensive strategy in accordance with the end use and the environment.

Figure 3 — RCPS can be used in horizontal floor applications as well as vertical wall applications.

3. Basics of Thermal Resistance

Basic thermal insulation knowledge begins with a fundamental understanding of heat flow. Arguably, from the viewpoint of a building engineer or architect, the most important material property of RCPS insulation foam board is its thermal resistance.

The heat flow (Q) per unit area (A) is directly proportional to the temperature difference (ΔT) divided by the thermal resistance (R_{th}).

$$q = Q/A = \Delta T/R_{th}$$

R_{th} equals the R-value. R_{th} values add in series, similar to electrical resistors. R-value is sometimes expressed as R-10 or R-20 etc., indicating the product of the R-value per inch and the thickness of the board in inches.

The Federal Trade Commission (FTC) requires home insulation manufacturers, professional installers, new home sellers, and retailers to provide R-value information, based on the results of standard tests, to help inform consumers. The R-value Rule is formally known as the "Trade Regulation Rule Concerning the Labeling and Advertising of Home Insulation." [7]

The reciprocal of thermal resistance is thermal conductivity [8]. See sidebar for an explanation of units, including how to convert between Imperial Units (Inch-Pound) and SI units for thermal resistance.

4. Making Sense of ASTM Types

Next, polystyrene foam knowledge requires understanding the fourteen RCPS classification types listed in Table 1 of ASTM C578.

Types XI, I, VIII, II, IX, XIV and XV make up the first seven columns and Types XII, X, XIII, IV, VI, VII and V make up the next seven columns. One could draw a line between columns 7 and 8 (i.e., between types XV and XII) to cleanly separate typically EPS insulations from typically XPS insulations. (Type III has been discontinued; hence the fourteen types include I through XV with Type III omitted. This discussion also omits Type XIII, a specialized Type of RCPS for pipe insulations.)

ASTM C578 does not demand that the any given Type be EPS or XPS. For example, there is no requirement that Type X *must* be XPS or that Type XII *must* be EPS. As long as the product meets the standard, it can qualify as a given Type. Realistically, however, there is widespread industry agreement regarding "EPS types" and "XPS types." It is quite rare for a manufacturer to market an XPS product as one of the EPS types. The paper ignores those rare exceptions and informally refers to EPS types and XPS types.

Although the Roman numerals appear to be in random order, there is a logic to the table. The types are sorted first by EPS or XPS and next by the specified minimum value for compressive resistance. Indeed, the first row gives the compressive resistance for each of the 14 types, ranging from 5.0 to 60.0 psi for the EPS types and from 15.0 to 100.0 psi for XPS types.

The first row in Table I of ASTM C578 gives the standard for minimal compressive resistance because compressive resistance is an important physical property for specifiers. Compressive resistance determines how much load can be placed on the RCPS foam board. Although 100 psi is only a fraction of the compressive resistance of steel (25,000 psi) or concrete (up to 10,000 psi) the compressive resistance of the foam boards could be a key specification for a protected membrane roof assembly, a basement floor, or an airport runway, to give a few examples. Obviously, RCPS foam board is not meant to be a structural material but when the load is distributed, then a compressive resistance of 100 psi could adequately support vehicular traffic in plaza decks or airplanes taking off from or landing on an insulated airport runway.

5. Typical R-values

The second row in Table 1 of C578 gives the minimal thermal resistance as measured at 75 °F. Thermal resistance varies significantly with temperature. In general, the R-value of RCPS decreases as the temperature increases. In other words, R-values are consistently higher at 25 °F and 40 °F compared to 75 °F and 110 °F for both EPS and XPS types. (Fig. 4).

The ASTM table that recommends minimal R-values at 25 °F, 40 °F and 110 °F is relegated to Table X1.1 in Appendix X1 along with other “Nonmandatory Information” in ASTM C578. Certainly, these higher R-values at lower temperatures are extremely relevant to specifiers selecting insulation for colder climate zones or environments.

At each of the test temperatures, five of the XPS types (X, IV, VI, VII and V) are specified to have the same minimum R-values per inch, which plateau at 5.60, 5.4, 5.0 and 4.65 for temperatures of 25 °F, 40 °F, 75 °F and 110 °F, respectively. That’s remarkable considering that other performance characteristics vary substantially for these five XPS types. It is evident that R-values have less correlation with density for XPS types and a much stronger correlation for EPS types. Furthermore, Figure 5 shows that the R-values for XPS types are consistently higher than the R-values for EPS types of similar densities.

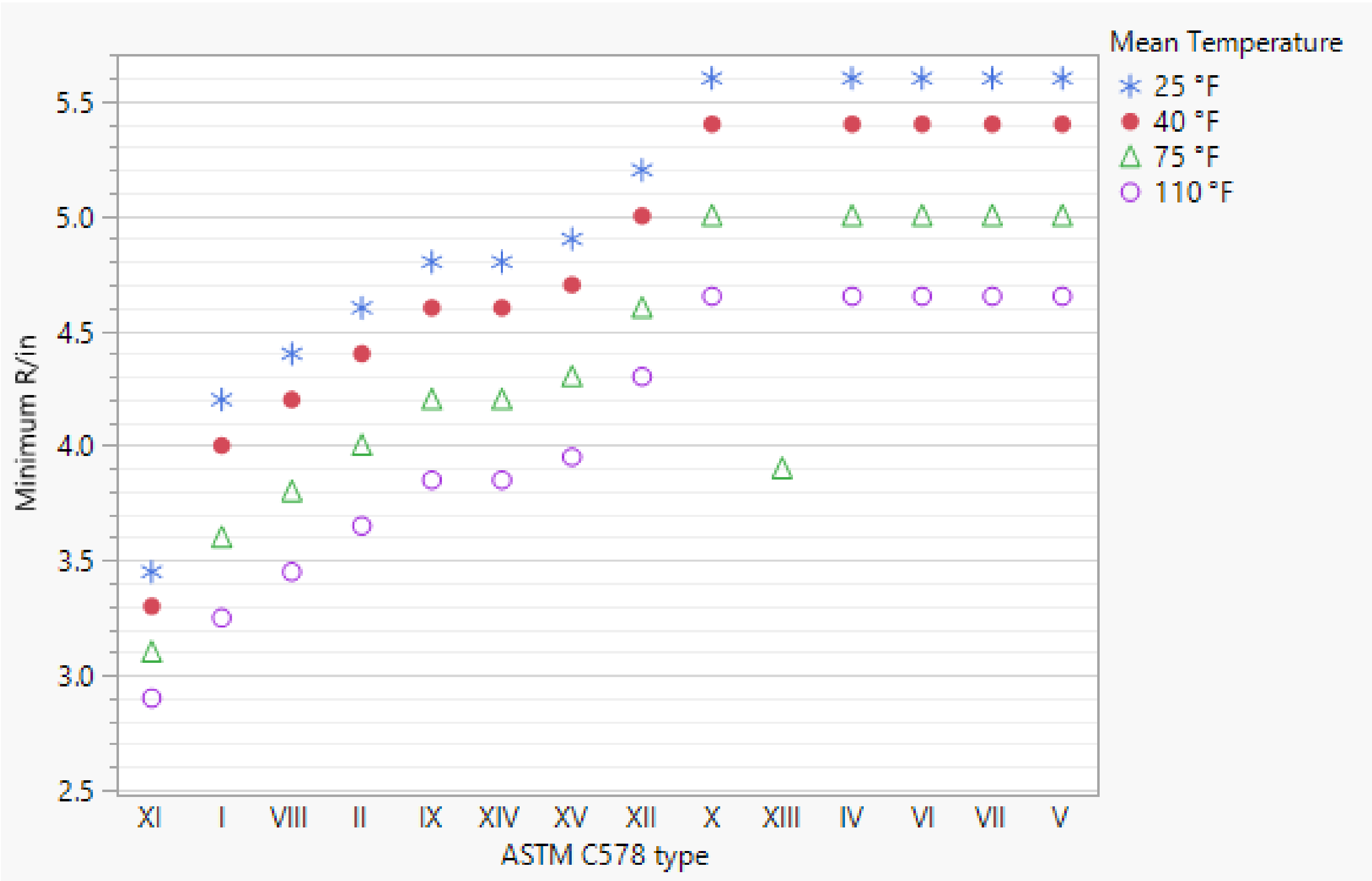
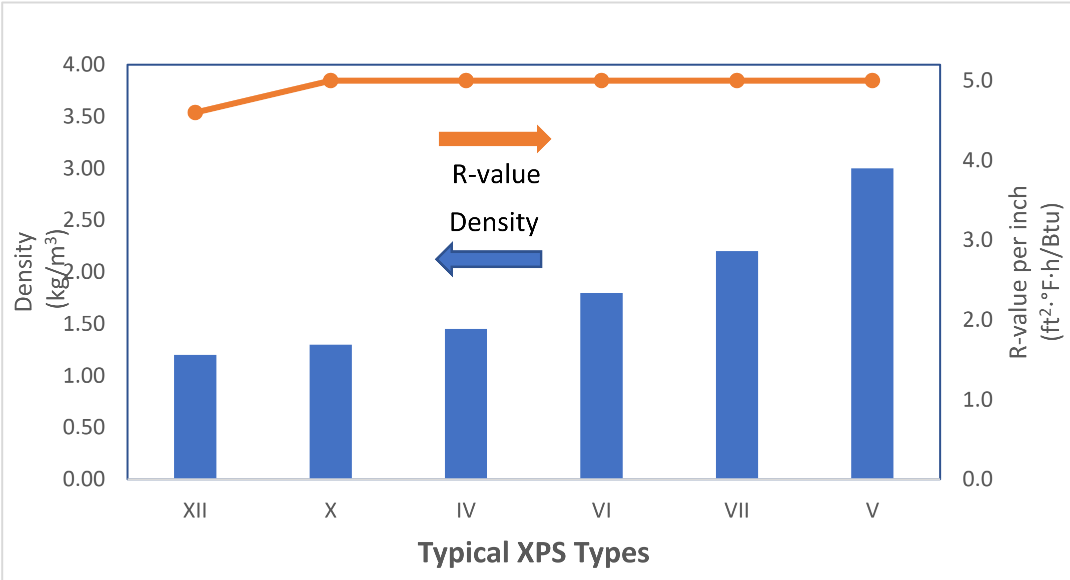


Figure 4 — R-value per inch increases as temperature decreases for both EPS and XPS ASTM Types.

Density is perhaps the least interesting material property for engineers and architects. The additional load on a building from the weight of RCPS foam boards is negligible. The only relevance of density may be in calculating the buoyancy of the foam boards when used on a protected membrane roof assembly (PMRA) or a flotation device. There will need to be enough ballast to keep the foam boards from floating. Also, the weight of the PMRA is relevant to the design for wind uplift resistance.



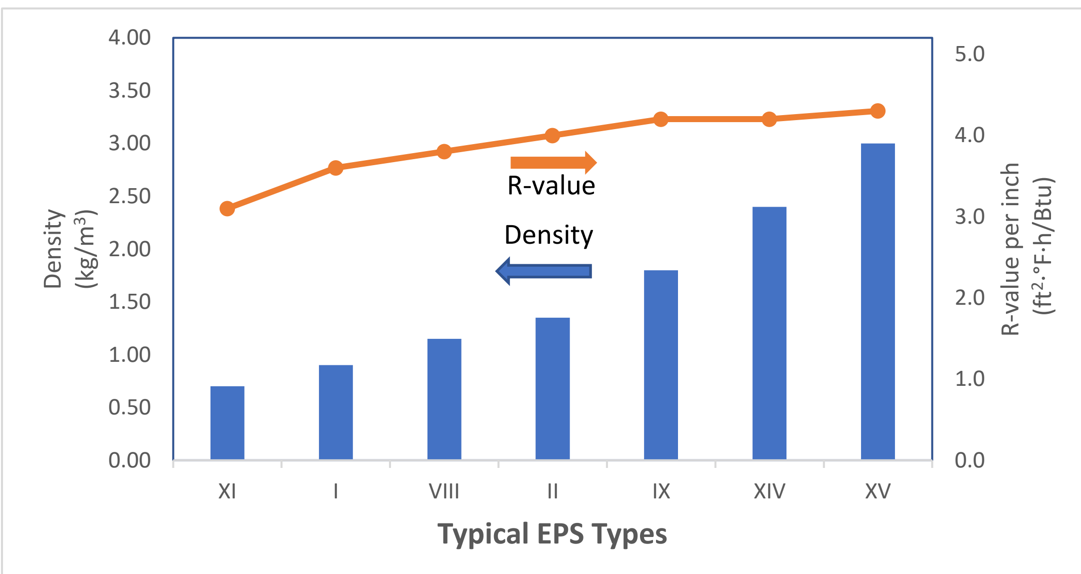


Figure 5 – R-value increases with density for both XPS and EPS Types, although R-value peaks at higher value and relatively low density for XPS Types. Values from ASTM C578 [4].

6. Porosity and Strength

Although density is not much interest to architects and engineers, it is noteworthy that material's strength correlates well with density. There are two observations worth noting:

1) Compressive strength and flexural strength generally correlate with density.
2) For a given density, XPS types are stronger than EPS types.

For example, XPS Type V and EPS Type XV both must test to a minimal density of 3.0 lbs/ft^3. Yet the compressive strength is 40 percent less for of the EPS Type compared to the XPS Type.

How could two foam boards of the same material with the same density have such different strengths? One possible answer may have to do with the *porosity*, which can be subdivided into *closed* porosity and *open* porosity.

Porosity is simply defined as one minus the ratio between the density of the foam and the density of the solid. According to NIST [9], the density of solid polystyrene (not insulation) is 1060 kg/m^3, which is slightly denser than water. (Of course, solid polystyrene has zero porosity.) Yet the density of polystyrene foam insulation boards ranges between 12 kg/m^3 and 48 kg/m^3; and hence the *total porosity* ranges between 0.99 percent (least dense) and 0.95 percent (most dense).

Table 1 of this paper shows the density and calculated *total porosity* of various types of RCPS along with the compressive strengths as given in Table 1 of C578. As density increases then the porosity decreases yet this does not explain the strength differences between EPS types and XPS types of similar porosity.

Total porosity is the sum of *closed porosity* and *open porosity*. Open porosity can be measured by the gas adsorption method: the more gas adsorbed, the greater the open porosity. Open porosity also explains the greater water absorption and permeability of EPS types compared to XPS types of the same density. The inference is that when the resin beads are expanded into a closed mold, the channels between the beads account for the higher open porosity. Although the cell wall thickness may be similar in EPS and XPS samples of similar density, the EPS would have a higher fraction of open porosity compared to closed porosity. Most porosity of XPS Types is closed porosity whereas a substantial fraction of the porosity of EPS Types is open porosity.

The open porosity of the EPS bulk matrix has a deleterious effect on strength and explains the higher water absorption of EPS foam board compared to XPS foam. Porosity is not the only factor underlying strength. Foam structure on the scale of the cells also is a factor. Mechanical strength is believed to come from polystyrene struts, which offer greater strength than the cell windows. A detailed discussion of how struts can strengthen RCPS is beyond the scope of this paper. Interested readers are referred to the technical literature on this topic [10]. Suffice it to say here that the strength of foam board is important for many applications of RCPS and manufacturers are continually seek to improve this property (Fig. 7).

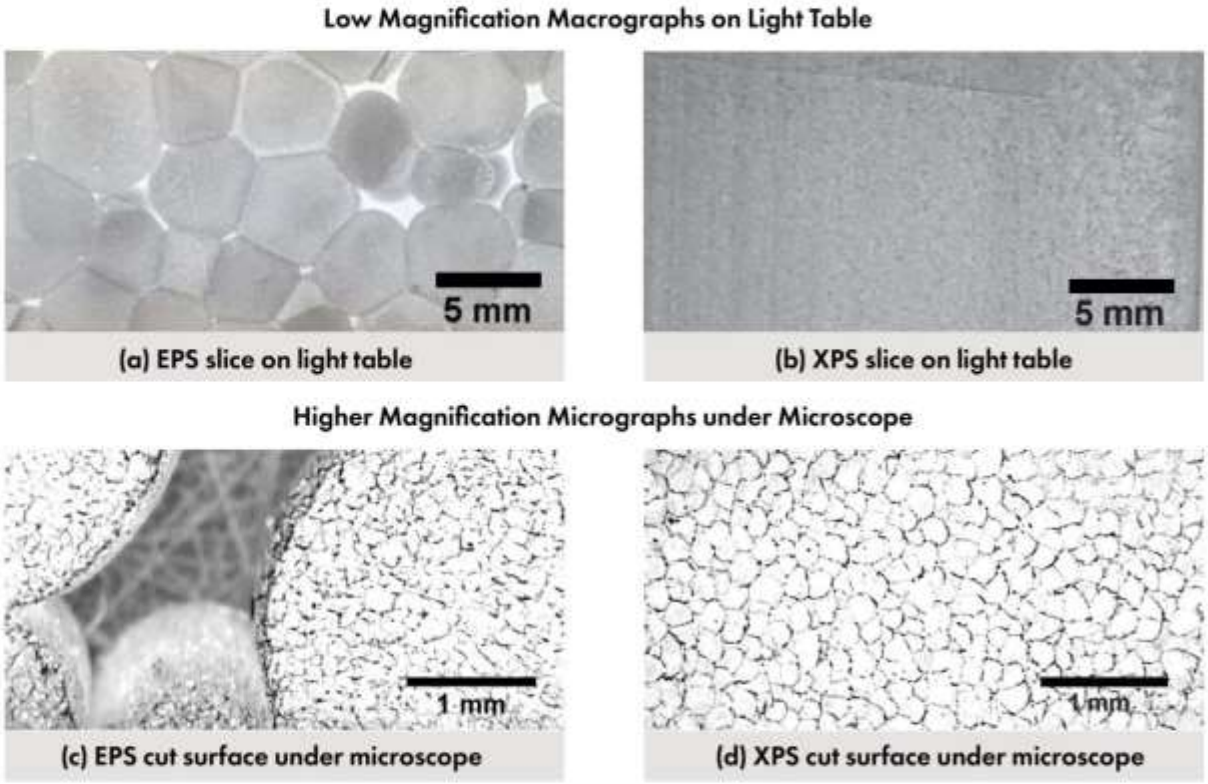


Figure 6 —EPS foam illustration has considerable open porosity compared to XPS foam insulation.

Figure 7 — Aerial view of U.S. Coast Guard Headquarters. XPS insulation must resist compressive loads from the weight of vegetative or "green" roofs. The appearance of U.S. Department of Defense (DoD) visual information does not imply or constitute DoD endorsement.

Table 1 — Calculated Total Porosity of XPS and EPS Types Based on ASTM C578 Minimum Density Values.

EPS Types							
Type	**XI**	**I**	**VIII**	**II**	**IX**	**XIV**	**XV**
Porosity $1-\rho/\rho_{solid}$	0.989	0.986	0.983	0.979	0.972	0.964	0.954
Compressive Resistance, min, psi	5	10	13	15	25	40	60
Flexural Strength, min, psi	10	25	30	35	50	60	75

XPS Types						
Type	**XII**	**X**	**IV**	**VI**	**VII**	**V**
Porosity $1-\rho/\rho_{solid}$	0.982	0.98	0.978	0.972	0.967	0.954
Compressive Resistance, min, psi	15	15	25	40	60	100
Flexural Strength, min, psi	40	40	50	60	75	100

7. The Truth about Water Absorption

The most startling numbers in ASTM C578 are found in the row on water absorption. These numbers represent the maximum water absorption allowed to meet the standard for each of the RCPS types. There is no question that EPS absorbs much more water than XPS, specifically in short-term testing by total immersion. Maximum values of two, three and even four percent by volume are seen for EPS Types. In general, for EPS, as density increases the maximum value is reduced but it does not drop below two percent by volume (Fig. 8).

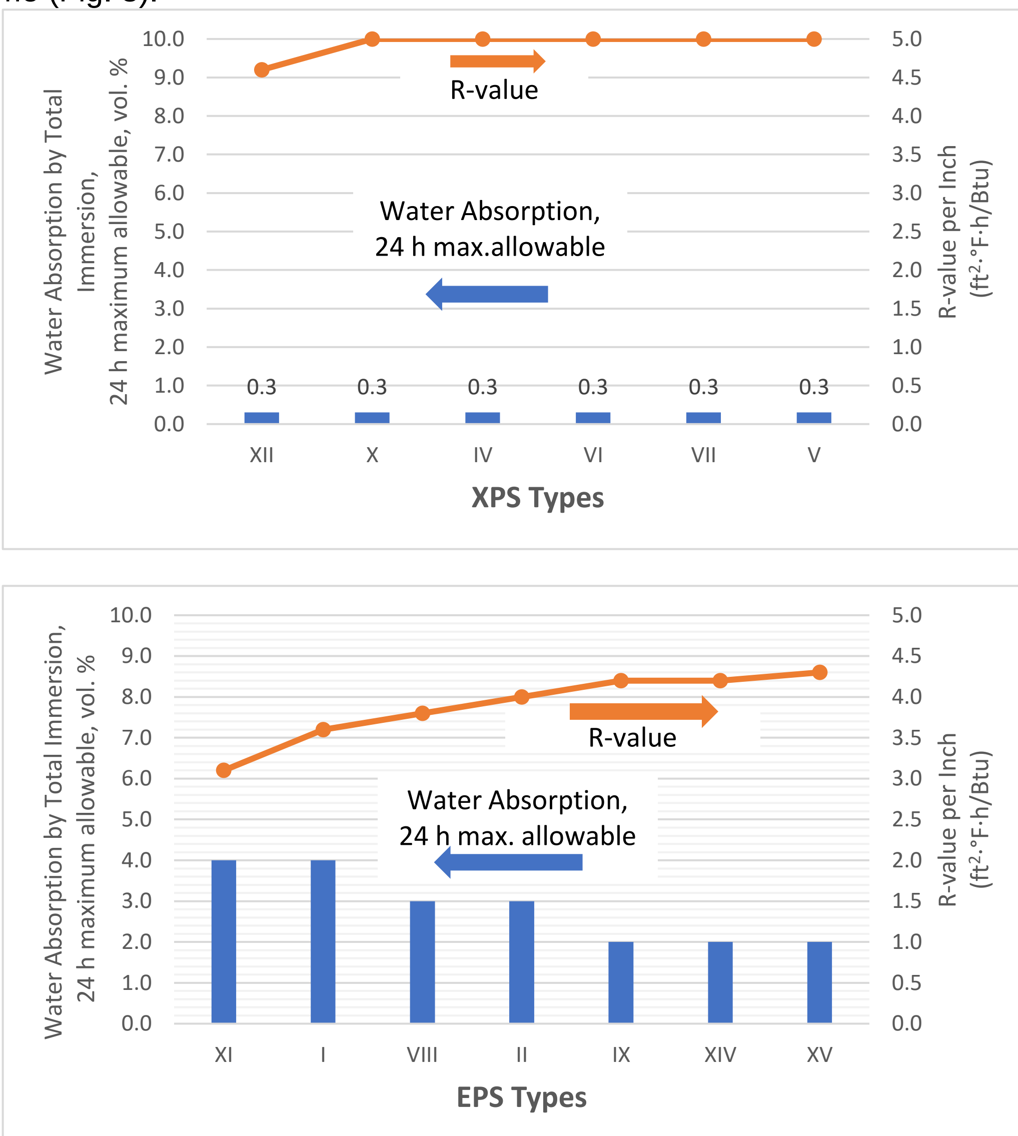


Figure 8 – R-value per inch increases as water absorption decreases. The high R-values for XPS could be attributed in part to its low values of water absorption. Water absorption is given in volume percent. Values from ASTM C578 [4].

One cubic meter of water weighs 1000 kilograms. When two volume percent of a cubic meter of Type XV foam are occupied by water, 20 kilograms of water are added to the 48 kilograms of foam. Values for water absorption per test method ASTM C272 for EPS types XI and I (up to 4 percent by volume), EPS types VIII and II (3 percent) and EPS types IX, IV and XV (2 percent) are in sharp contrast to the maximum water absorption for XPS types XII, X, IV, VI, VII and V (maximum 0.3 percent by volume).

In other words, depending on the specific type, EPS is allowed to absorb seven to ten times as much water as XPS and still meet the ASTM C578 product standard. See Table 2 in this paper.

This water absorption rate even for short term testing represents a major difference between EPS and XPS RCPS foams. ASTM C578 requires manufacturers to meet the water absorption limits for relatively short periods of immersion. Additionally, ASTM C578 mentions in the Appendix X1.4 Water Absorption that "This characteristic may have significance when this specification is used to purchase material for end-uses requiring extended exposure to water." This Appendix is however considered "Nonmandatory Information" and no attempt is made to quantify the effects of this water absorption on the thermal performance of the materials. Designers are left to their own resources.

Table 2 – Water absorption for various polystyrene EPS and XPS Types

	Water Absorption by total immersion, 24 h max absorbed (volume %)
EPS Types	
XI and I	4.0
VIII and II	3.0
IX, XIV and XV	2.0
XPS Types	
XII, X, IV, VI, VII and V	0.3
XIII	1.0

The *reason* for this disparity has to do with the discontinuous structure of EPS foam boards, which results in significant open porosity as described in the previous section. The capillary pathways allow water to enter the EPS types throughout the bulk of the material, depending on the capillary sizes. Smaller bead sizes – such as are used in food grade EPS – result in smaller and less permeable capillaries, but such also limit the density reduction. On the contrary, relatively little water enters the bulk of the XPS samples because its high closed-cell porosity inhibits the absorption of water. XPS insulation has a smooth microstructure that is not interrupted by the millimeter-scale “bead structure” prevalent in EPS types.

The consequences of water absorption can be severe depending on the application. It is one of the main reasons why EPS is unsuitable for protected membrane roofing assemblies (PMRA) [1]. It also explains why XPS is preferred in below grade applications. Also, for habitable basements, where the polystyrene insulation is commonly applied exterior to the basement walls and floor slabs (and thus often in contact with ground water or moist soils), XPS is preferred over EPS [2].

The mechanisms of water absorption are reviewed in considerable detail in the XPS Insulation performance white paper titled “Effects of Moisture Absorption Mechanisms on In-Service Design R-values of Polystyrene Insulation” [11]. See also See also . Pakkala, Jukka Lahdensivu [12].

8. Myths about Testing for Water Absorption

Aside from the water absorption mechanisms, which in general are not disputed, several myths and misinterpretations have developed concerning water absorption testing. The crux of the problem is the conflation of the ASTM C578 standard with performance expectations. ASTM C578 does not dictate the thickness of insulation required to achieve long-term design R-values. That is based on engineering judgment using various thickness correction guidelines.

(1) Most experts readily acknowledge that R-values drop as water is absorbed. This is based on simple physics. The thermal conductivity of water or ice is much higher than the thermal conductivity of air or blowing agents. Performance has been simulated using computer models [13, 14]. Nonetheless, the prediction of water absorption depends on the application, the climate zone and other factors.

(2) Some have argued that water absorption does not really matter because the insulation quickly dries out. This is untrue in many cases, especially for below grade applications as described in the XPSA Insulation Performance white paper titled “Extruded Polystyrene Delivers Higher R-values than Expanded Polystyrene in Below-Grade Applications, According to New University of Alaska Fairbanks Study.” [3]

(3) It is also argued that there is an upper limit to the amount of water that can be absorbed. This is not at all true, according to a meta-analysis of field studies reported by Cai et al. [15, 16].

Specifiers must keep in mind that the short-term testing for moisture absorption utilized in ASTM C578 does not predict how moisture absorption affects performance in different applications. There is a heavy energy waste penalty due to reduced R-value when the insulation is used in wet environments such as building foundations, protected membrane roofing assemblies, infrastructure in cold regions, and other below grade applications. It is up to the specifier or consultant to account for the consequences of material choices in any given application.

ASTM C578 only gives basic properties of the various types of EPS and XPS at the time of manufacture. In the final analysis, the architect, engineer, consultant or specifier must exercise “engineering judgment” in the design of insulation systems suitable for a particular application and environment. Thermal stability, moisture control, thickness factor, long-term R-values and so on are all relevant to the design of below grade structures.

9. Concluding Remarks: Facts and Caveats

Insulation products are essential for improving the energy efficiency and service life of buildings. Polystyrene foam insulation boards are among the most versatile insulation materials available. However, not all polystyrene insulations are created equal. ASTM C578 has raised awareness that there are two distinct types of polystyrene insulation boards, including EPS and XPS, and, in general, these two classes of insulation have very different properties.

ASTM C578 gives the facts but leaves the door open for logical fallacies. *Caveat emptor* (buyer beware!) rules the marketplace. There are many weak arguments presented that would suggest that the short-term moisture absorption values in ASTM C578 represent an upper limit on the moisture absorption. There are also thinly reasoned arguments that moisture absorption “doesn’t matter” because the insulation dries out. These are valid points for investigation but without standard testing and in-field observations, marketing campaigns may advance anecdotal “evidence” of performance in insulation friendly environments. Until reliable long-term testing and modeling can be developed, engineering judgment will continue to play a vital role in the specification of insulation.

SIDEBAR ON UNITS

A full understanding of "R-value" is essential to the application of ASTM C578. Here is a review of the basic of thermal resistance values and how to convert from Imperial units to RSI units.

Heat Flow per unit area: $Q/A = \Delta T/R$
R = R-value per unit thickness (times thickness)
Rearranging the Heat Flow equation gives the following equation for R-value
$R = (\Delta T/Q) \cdot A$

In Imperial Units:

Q has units of energy per unit time, or BTU/h
ΔT has units of degrees Fahrenheit , or °F
Area has units of square feet, ft^2
Therefore, R-value per unit length has units of $(ft^2 \times °F)/(BTU/h) = (°F \times ft^2 \times h/BTU)$

Similarly, in SI units, "RSI" has units of $°C \times m^2/W$ or equivalently $K \times m^2/W$

Converting from I-P to SI Units

To convert from Inch-Pound units to SI units, apply the following conversions.

1 °F = (5/9) K
1 Btu/h = 0.2931 W
1 ft^2 = 0.0929 m^2

$°F \times ft^2 \times h/BTU = (5/9) \times 0.0929/0.2931\ K.m^2/W$

$(°F \times ft^2 \times h/BTU) / (K \times m^2/W) = 0.176$

$(K \times m^2/W) / (°F \times ft^2 \times h/BTU) = 5.678$

R-value (in I-P) ≈ RSI-value (in SI) × 5.678
RSI-value (in SI) ≈ R-value (in I-P) × 0.176

To convert to an RSI value in SI Units an R-value in Inch-Pound units, multiply by 5.678
To convert an R-value in Inch-Pound units to an RSI value in SI Units, multiply by 0.176

About thermal conductivity

Inversely, the U-value for an insulator is a measure of thermal conductivity. The inverse of the R-value is also known as the overall heat transfer coefficient.

U-value = (1/R-value) = heat flux / (temperature difference). For a given temperature difference, a high U-value signifies a high heat flux. The heat flux in Imperial units is expressed as BTUs per hour per square foot; and in SI units, the heat flux is expressed as watts per square meter. The total heat transferred would be the heat flux times the area. Heat flow is greatest through areas with low R-values. U-value of an assembly – such as a wall or entire building envelope – accounts for individual U-values and interplay of the assembly components.

A simple example

The R-value for one inch thickness of most materials is less than 1 °F × ft^2 × h/BTU. Consider a one-square-foot, one-inch-thick block of material with a 10 °F temperature differential on either side of the block.

If the R-value per inch has a value of 1 °F ×ft^2 ×h/BTU then this block would transfer 10 BTUs every hour.

If the block area were 10 ft x 10 ft, then the heat loss would be 1000 BTUs per hour. Increasing this example to 1000 ft^2 (equivalent to the wall area of a small double-wide) results in 10,000 BTUs every hour or 240,000 BTU per day. Poorly insulated homes are notoriously expensive to heat and cool for this reason. In our example, energy loss adds up to $3-7/day (or $1,000-$10,000 per year, accounting for seasonal, fuel type, and regional variability).

At the other extreme, an XPS foam board typically has a thermal resistance five times greater than our hypothetical material. So, in the example, instead of transferring 1000 BTUs, it would only transfer 200 BTUs. Moreover, five inches would only transfer 40 BTUs. It is easy to see how polystyrene insulation can dramatically inhibit heat transfer through walls, floor slabs and roofs and reduce energy use and waste. Few building materials offer as high values of thermal insulation as polystyrene insulation.

END OF SIDEBAR ON UNITS

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