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MOISTURE ACCUMULATION IN EXPOSED EXTRUDED POLYSTYRENE INSULATION IN WESTERN CANADA

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ABSTRACT

Extruded polystyrene (XPS) insulation has been installed in protected membrane roof (PMR) assemblies for more than 40 years. The benefits of the PMR assembly include a continuous insulation layer and protection of the waterproofing membrane from thermal cycling; however, the insulation must meet the durability requirements of being exposed to environmental conditions. In data obtained from PMRs across western and central Canada, XPS samples were found to have ranges of water accumulation from low to high moisture contents after a range of years in service. The data include wet and dry densities, as well as the measured heat transfer coefficients of samples obtained from existing PMR assemblies. The data indicate that closed-cell insulations such as XPS in plaza, parkade, and roofing PMRs may absorb moisture over their service lives and, in some cases, compromise the energy performance of the assembly. As determined in previous studies, the effects of moisture accumulation in insulation include a reduced thermal resistance and an increased load on the structure. These data will begin to provide some correlations between PMR assemblies that result in moisture accumulation and PMRs that retain low moisture contents over their service lives.

SPEAKER

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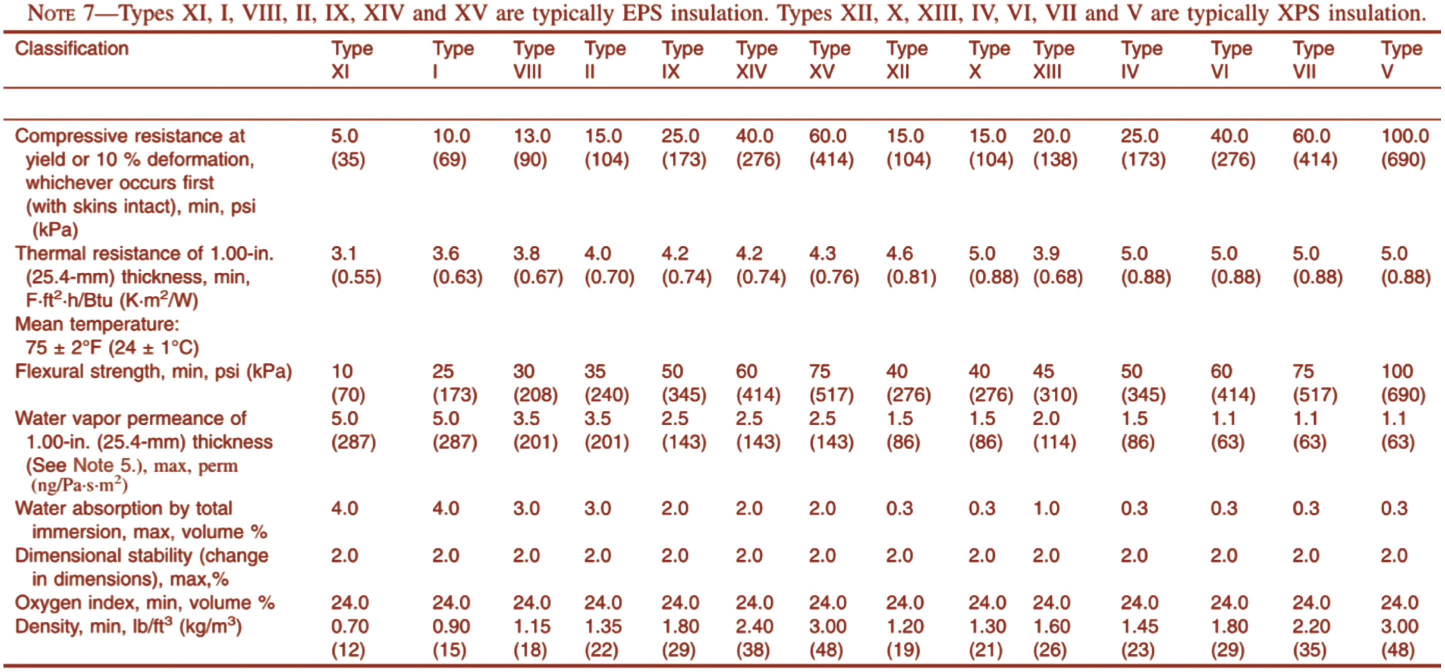
INTRODUCTION

The protected membrane roofing (PMR) assembly is designed to protect the roofing membrane from exposure to weather-related thermal stresses, ultraviolet (UV) radiation, and mechanical damage (RCABC, 2016, Smith, T. 2014). PMR systems are commonly used for low-slope roofing, plaza roofing, and vegetative roofing assemblies. The assembly consists of a roofing membrane below layers of insulation and a layer of ballast that may consist of aggregate, concrete, pavers, or soil for vegetative roofing. Ballast and insulation layers may be combined to form products like concrete or mortar-faced XPS panels. The placement of the insulation layers maintains the roofing membrane at a temperature closer to the interior temperature, reducing the thermal cycling temperature extremes of the membrane and extending the membrane's life expectancy (Dechow et al. 1978, Basham et al. 1999). Basham stated that only certain insulations are suitable in the PMR's wet or exposed environment. The PMR design also provides a continuous thermal barrier exterior to the structure and other critical building envelope elements.

XPS has been installed in PMRs for about 45 years and is currently a standard product for assemblies with insulation exposed to the exterior environmental conditions. In some roofing assemblies, the XPS insulation is exposed to conditions that result in moisture accumulation while in service. Previous research includes laboratory and field performance measurements of insulation performance exposure to exterior environments (Dechow et al. 1978, Sandberg 1986, Tobiansson et al. 1991, Kunzel and Kiesl 1997, Crandell 2010). Through calculation of results with measurement support, Kunzel and Kiesl found that moisture performance of XPS depends on the mean relative humidity (RH) at the upper surface of the insulation. The results determined that exposure of XPS to 90% humidity in summer would result in moisture absorption and moisture accumulation with yearly cycles. At higher RH values, the rate of moisture accumulation increases. Tobiansson et al. studied the thermal resistance ratio of insulation materials under wet and dry conditions and determined that as moisture accumulates in an insulation, its thermal resistance decreases. Dechow et al. reviewed laboratory experiments and field service data over a period of ten years on many insulation types and concluded that XPS had the best thermal performance due to its resistance to water absorption. Dechow noted that XPS insulation's thermal resistance would be reduced as it absorbed water, and that to be considered non-deficient, XPS should be expected to maintain at least 80% of its thermal resistance for a ten-year period. In a building energy-saving study, Kehrer et al. in 2012 retrieved field samples from foundation walls after 15 years and determined that moisture accumulation in XPS had an influence on the long-term energy performance of the roofing assembly. Kehrer also concluded that XPS and expanded polystyrene (EPS) recovered their properties after drying, indicating no significant aging had occurred except for the accumulation of moisture. Overall, the research concluded that changes in the moisture content of XPS should be considered as a factor in the durability of a roofing assembly's thermal performance.

Field observations of roofing assemblies have established that components of the roofing below the ballast may remain


NOTE 7—Types XI, I, VIII, II, IX, XIV and XV are typically EPS insulation. Types XII, X, XIII, IV, VI, VII and V are typically XPS insulation.

Classification	Type XI	Type I	Type VIII	Type II	Type IX	Type XIV	Type XV	Type XII	Type X	Type XIII	Type IV	Type VI	Type VII	Type V
Compressive resistance at yield or 10 % deformation, whichever occurs first (with skins intact), min, psi (kPa)	5.0 (35)	10.0 (69)	13.0 (90)	15.0 (104)	25.0 (173)	40.0 (276)	60.0 (414)	15.0 (104)	15.0 (104)	20.0 (138)	25.0 (173)	40.0 (276)	60.0 (414)	100.0 (690)
Thermal resistance of 1.00-in. (25.4-mm) thickness, min, F·ft^2·h/Btu (K·m^2/W) Mean temperature: 75 ± 2°F (24 ± 1°C)	3.1 (0.55)	3.6 (0.63)	3.8 (0.67)	4.0 (0.70)	4.2 (0.74)	4.2 (0.74)	4.3 (0.76)	4.6 (0.81)	5.0 (0.88)	3.9 (0.68)	5.0 (0.88)	5.0 (0.88)	5.0 (0.88)	5.0 (0.88)
Flexural strength, min, psi (kPa)	10 (70)	25 (173)	30 (208)	35 (240)	50 (345)	60 (414)	75 (517)	40 (276)	40 (276)	45 (310)	50 (345)	60 (414)	75 (517)	100 (690)
Water vapor permeance of 1.00-in. (25.4-mm) thickness (See Note 5.), max, perm (ng/Pa·s·m^2)	5.0 (287)	5.0 (287)	3.5 (201)	3.5 (201)	2.5 (143)	2.5 (143)	2.5 (143)	1.5 (86)	1.5 (86)	2.0 (114)	1.5 (86)	1.1 (63)	1.1 (63)	1.1 (63)
Water absorption by total immersion, max, volume %	4.0	4.0	3.0	3.0	2.0	2.0	2.0	0.3	0.3	1.0	0.3	0.3	0.3	0.3
Dimensional stability (change in dimensions), max,%	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Oxygen index, min, volume %	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0
Density, min, lb/ft^3 (kg/m^3)	0.70 (12)	0.90 (15)	1.15 (18)	1.35 (22)	1.80 (29)	2.40 (38)	3.00 (48)	1.20 (19)	1.30 (21)	1.60 (26)	1.45 (23)	1.80 (29)	2.20 (35)	3.00 (48)

Table 1 – Properties of various XPS insulation types, from ASTM C578-17A.

Figure 1 – Local site sampling procedure.

damp or wet while in service, and that the weight of the insulation layer increases as it absorbs water. As engineering design relies upon the relatively dry values for XPS thermal performance and material density, the resulting degradation of the thermal resistance and increased loading of the structure due to water accumulation should be considered. This paper presents data from an ongoing field sample study on the measured physical properties of insulation samples retrieved from PMRs with known years in service ranging from 11 to 38 years. Measured properties include wet densities and thermal resistance values from a 2017 study by C. Tougas et al. (2017) on the thermal performance of XPS samples from in-service roofing assemblies. In contrast, the resulting wet and dry properties from a 2016 study by Peer and Tariku, (referred to as "2016 Study"), have been included for comparison. The main objective of these studies is to correlate relationships between existing roofing assemblies and the measured properties of XPS samples, including their moisture accumulation and thermal conductivity. (See *Table 1*.) To achieve this objective, the following tests were performed:

1. **Thermal conductivity measurement.** Using a heat flow meter (HFM), measure the thermal conductivity of XPS insulation samples obtained from in-service roofing assemblies.
2. **Moisture content (MC) of field samples.** Determine the amount of water absorbed by the XPS samples while in service. The moisture content and thermal conductivity data are used to develop a relationship between the results.
3. **Drying of samples to determine the dry density.** This is ongoing; where dry density samples have not been determined, an estimate of the MC values was determined using the average dry densities from the 2016 Study or manufacturers' technical datasheets for labeled samples.

Test Samples

Test samples were retrieved from in-service roofing assemblies or during roofing replacement projects from 2015 to 2017 in western Canada (*Figure 1*). Site samples were provided randomly based on their availability during assessment services or as provided voluntarily by contractors during roofing replacement projects.

Typical roofing assemblies include:

- Two roofing assemblies with aggregate ballast
- One roofing assembly with 2-in. continuous concrete pavers on pedestals
- One roofing assembly with a continuous concrete slab
- One roofing assembly with bedding sand and brick pavers
- One roofing assembly with built-in drainage layers
- Three roofing assemblies with 0.5 to 2% slope

The site assemblies had similar design conditions:

- They were installed over membranes over heated enclosures under concrete toppings.
- The assemblies did not have drainage mats above or beneath the insulation.
- The climate conditions likely kept the assemblies at high RH for significant periods of the year.

Table 2 provides a site overview, including locations, conditions, and roof areas. Conditions include exposure to sun or shade, drainage performance due to proximity of drains and organic build-up, and continuity and vapor permeability of ballast layers. See *Figure 1* for example sampling conditions.

EXPERIMENTAL SETUP

Sample Preparation

Samples of insulation removed from the roofing assemblies in British Columbia (BC) were wrapped in 3-mil polyethylene bags and sealed with red sheathing tape before transfer to the British Columbia Institute of Technology (BCIT) Building Science Lab for property measurement. Samples shipped from outside of BC were wrapped in tinfoil and polyethylene bags, each layer sealed with red sheathing tape, prior to shipping. Samples obtained from onsite in BC were weighed within 48 hours of procurement. Shipping times for samples from outside of BC took up to three days and consisted of ground-only transport to avoid exposing samples to high elevation conditions. Test samples for thermal conductivity and moisture content measurement were prepared from each XPS board as shown in *Figure 2.* A total of 52 samples for moisture content and thermal conductivity measurement

Site Location						Roofing	
Country	Province	Region	Climate Number	Site Address	*Terrain [NAFS]	Roofing Type	Roof Area [sq. m.]
Canada	AB	Calgary	7A	n/a	n/a	Exterior pedestrian plaza	N/A
	BC	Vancouver	4	n/a	n/a	Inverted roofing assembly	N/A
		Vancouver	4	n/a	n/a	Rooftop parking at mall	50
		Burnaby	4	n/a	n/a	5th-floor covered parking garage	25
		Vancouver	4	1130 West Pender St.	Open	Penthouse roof deck	400
		Vancouver	4	777 Dunsmuir St.	Open	Recreational plaza over mall	3500
		Burnaby	4	3777 Kingsway	Open	Inverted roofing assembly	1440
		Vancouver	4	885 West Georgia St.	Open	Inverted roofing assembly	320
		Vancouver	4	1100 Melville St.	Open	Inverted roofing assembly	156
		Victoria	4	6000 William Head Rd.	Rough	Inverted roofing assembly	312
		UBC	4	2259 Lower Mall #358	Open	Inverted roofing assembly	336
		UBC	4	2205 E. Mall	Rough	Inverted roof deck	45
	AB	U of C	7A	3120 31 St. NW	Rough	Inverted roofing assembly	750

Table 2 – Site overview.

Site Address	Dates		Slope (%)			Membrane						Drainage		Insulation			Components					
	Year of Installation	Years in Service	0	1.5	2	EPDM	2-Ply	1-Ply	PVC	BUR	Liquid-Applied	Below Insulation	Above Insulation	XPS Thickness	No. of Layers	Staggered	Concrete Slab	Polyethylene Slip Sheet	Pavers	Stone	Sand	Pedestals	Filter Fabric
n/a (2016 Study)	2003	11	✓				✓							50	1				✓		✓		
n/a (2016 Study)	1993	22			✓						✓			38	1				✓				✓
n/a (2016 Study)	1988	27		✓				✓						38	1		✓						
n/a (2016 Study)	1985	30			✓	✓								38	1		✓						
1130 West Pender St.	1980	37	✓				✓							50	1				✓		✓		✓
777 Dunsmuir St.	1989	28			✓			✓						50	1				✓			✓	✓
3777 Kingsway	1985	32	✓				✓							50	1		✓	✓		✓			✓
885 West Georgia St.	1985	32	✓					✓						50	1					✓			✓
1100 Melville St.	1985	32	✓					✓						50	1					✓			✓
6000 William Head Rd.	1979	38	✓				✓							50	1					✓			✓
2259 Lower Mall #358	n/a	30+	✓							✓				50	1					✓			
2205 E. Mall	n/a	30+	✓								✓			100	1				✓			✓	
3120 31 St. NW	n/a	30+	✓						✓					75	1				✓				

Table 3 – Roofing assembly checklist.

Figure 2 – Thermal conductivity and moisture content measurement sample preparation.

were prepared from 13 insulation boards for the 2016 study. To date, a total of 579 samples have been prepared from 67 XPS sample insulation boards obtained from various sites for conducting moisture content and thermal conductivity measurement for this ongoing study. The 300- by 300-mm (11.8- x 11.8-in.) thermal conductivity test samples were wrapped with 6-mil polyethylene film and sealed with tape to minimize moisture loss from the samples before and during measurements (*Figure 3*). For each thermal conductivity sample, three moisture content measurement samples with dimensions of 25 mm width and 100 mm length were prepared (*Figure 4*). Once the samples were cut, their initial weights, as well as their lengths, widths, and thicknesses were measured (*Figure 5*). The duration between removing samples from site and sample preparation varied from hours to several days, depending on the site location and HFM availability. The steps taken in preparing the samples were incorporated to maintain the sample conditions between the site and lab.

While the samples were being cut into the required sizes for the different tests, water appeared on the fresh-cut surfaces of the samples and blades with the heavier samples. This water was likely stored in closed cells within the XPS that released the water when the cells were cut into. Water would continue to bead on the surface for some time following the initial cut, suggesting that the water within the sample was under a pressure differential (*Figure 6*). The samples were not stored beneath the water table, so the pressure is thought to be due to capillary pressure within the sample that was relieved when the cross section was cut.

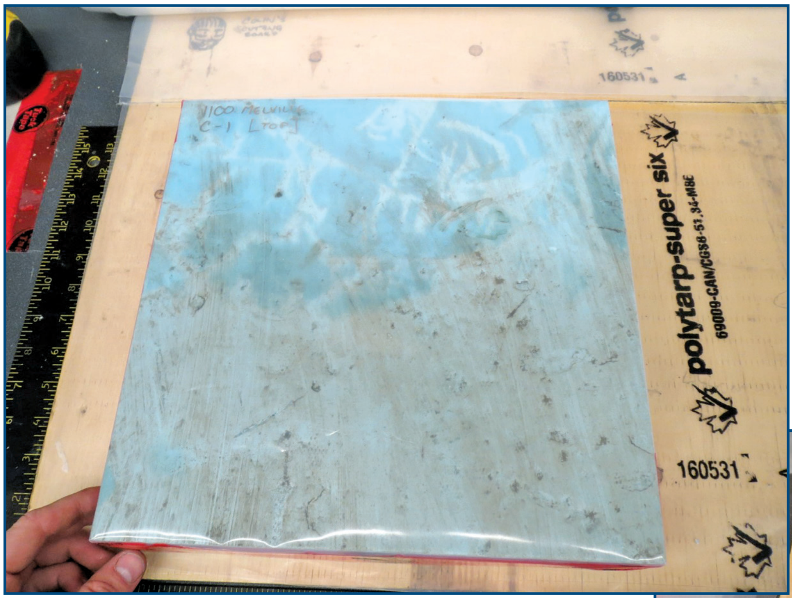


Figure 3 – Thermal conductivity test samples wrapped with 6-mil polyethylene.

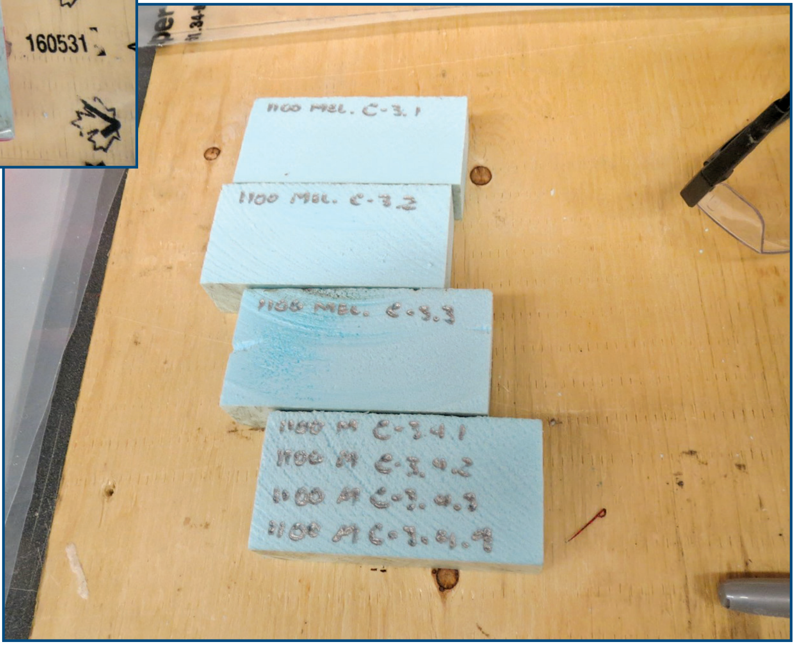


Figure 4 – Moisture content and moisture distribution samples.

Figure 6 – Freshly cut cross section of insulation.

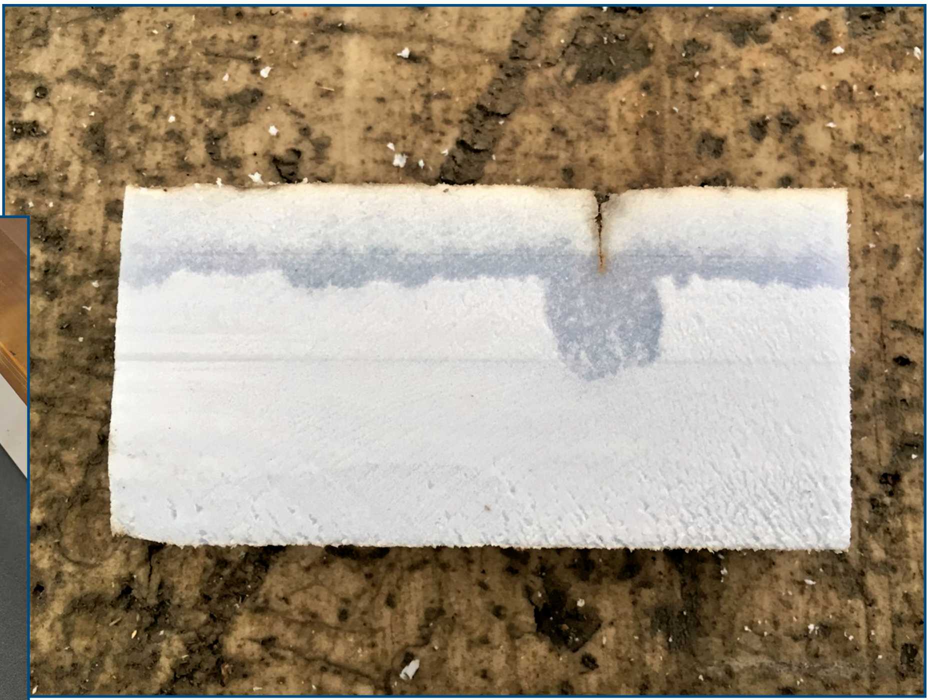
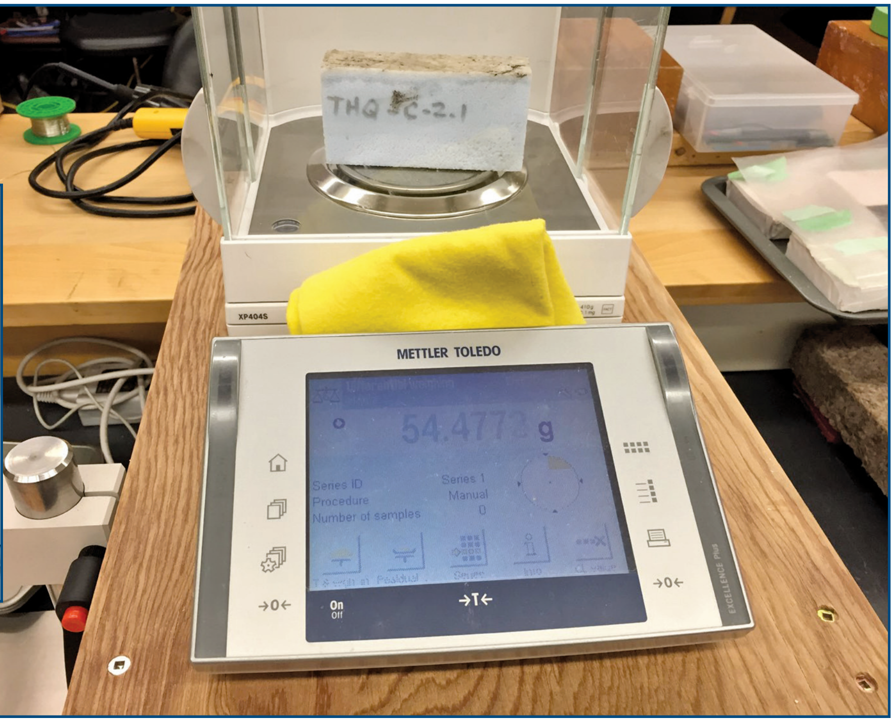


Figure 5 – Sample volumes measured.

Moisture Content Measurement

The MCs of the samples were determined by gravimetric means using a Veritas Analytical Balance, accurate to 0.0001 g, and a forced-air convection oven (*Figure 7*). After taking the initial weights of the samples, they were placed in the oven and left to dry at 70°C (158°F). Every 24 hours the samples were taken out of the oven, weighed, and put back into the oven for further drying until the samples were declared "dry." The samples were assumed to be at a dry state when three successive weight measurements were within 0.1% of being in conformance with the ASTM C1498 standard. The dry weights of a minimum of three samples cut out from each board were averaged to obtain the average dry mass of each piece of insulation board. Due to the long drying times of heavier samples, some of the dry densities have yet to be determined. In order to provide an estimate of the sample MC for this paper, the average dry density from the 2016 samples was used. The final values will be corrected when the dry densities are determined. It should also be noted that the majority of XPS samples obtained with identifiable labeling were Type IV, with a density of 32kg/m^3 as indicated on the product data sheet.

MC is reported as percentage by volume and by mass. Papers by Tobiasson, 1991 and Dechow, 1978, generally converted the



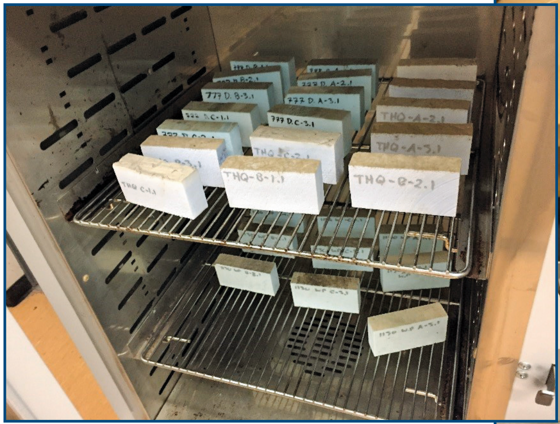


Figure 7 – A (above) Scale for measuring masses of samples and B (right) convection oven with drying samples.

measurements to percentage by volume for discussion. One reason for this approach is that the dry densities of insulations vary, so the mass percentage gain over the initial mass would be difficult to compare. Additionally, the high measured MCs relative to the low dry densities result in percentage mass values in the thousands of percentages at relatively low MC values, which does not provide for a meaningful comparison. The percentage MC by volume is a useful indicator of the degree of partial saturation of the sample—in effect, the amount of porosity in the samples that is occupied by water.

Moisture distributions across the samples were estimated by dividing the sample into thirds through the thickness of the sample (*Figure 4*), the dimensions measured to calculate the volume via a thickness gauge (*Figure 5*), and comparing the section weights to the total weights. Determining the moisture distribution through the sample provides some insight into the mechanism for moisture absorption.

Thermal Conductivity

The thermal conductivity of the 300-mm-long x 300-mm-wide test samples was measured using a Netzsch 436 Lambda HFM. According to the manufacturer's specification, the HFMs have an accuracy of ±1% and repeatability of ±0.3%. The measurements were carried out in accordance with ASTM C518-10, at mean temperature of 24°C (75°F) and temperature difference of 20°C (68°F). The test setup temperatures are listed in *Table 3*.

Prior to testing, the heat flow meter was calibrated at the test temperature conditions using a standard reference material (SRM 1450C432). The thermal conductivities of the samples were measured while they were wrapped with polyethylene sheets to restrict moisture from leaving the samples. A specialized software known as QLab was used to set up the test parameters, measure the thickness and the thermal conductivity of the samples, and record the intermediate and final test results through a computer interface. The thermal conductivity test runs until the software detects steady-state heat flow through the sample in successive measurements. The test results of at least three 300- x 300-mm samples from each sample location were used for this study, which sets the standard for an ongoing study by RJC and BCIT for a minimum sample size to determine the average thermal conductivity value at each location.

Mean temperature	24.0°C	(75.2°F)
Temperature difference	20.0°C	(68.0°F)
Upper temperature	34.0°C	(93.2°F)
Lower temperature	14.0°C	(57.2°F)

Table 3 – Testing setup of temperature and accuracy.

Update Rate	15 minutes
Rough Block Size	40 data points
Maximum Rough Error	1.0%
Fine Block Size	40 data points
Maximum Fine Error	0.2%

Table 4 – Testing setup for steady-state conditions.

RESULTS

Moisture Content

On a single roof area, moisture contents in the insulation boards appear to differ significantly from location to location. This may be due to varying micro-climate conditions or specific roofing details at the sampling locations. For example, the weights of samples from a one-year-old assembly ranged from 141.36 to 2,496.27 grams as shown in *Figure 8*, a weight ratio of approximately 17.6 between the samples. The weights of samples from a 32-year-old roof assembly ranged from 160 grams to 1791 grams as shown in *Table 4*, a weight ratio of approximately 11.2 between the samples.

Figure 8 – Weights of 11-year-old samples (2016 Study).

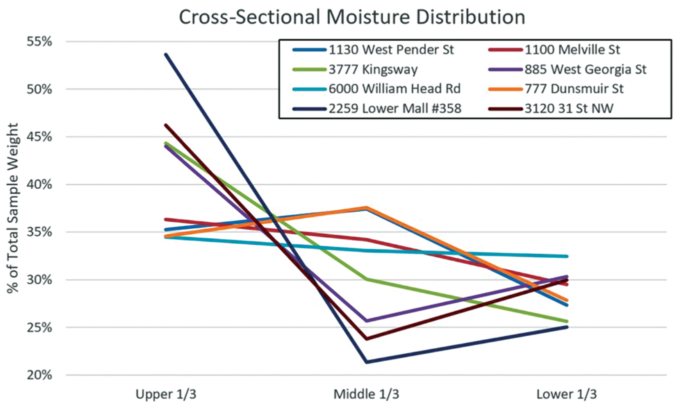


Figure 9 – Moisture distribution.

The moisture contents of exposed insulation samples, along with their corresponding oven-dry weights (2016 Study), are presented in *Table 4* and *Table 5*. The moisture content values in *Table 4* represent resulting measurements from the 2016 study. The sample densities were determined from their oven-dry mass and volume measurements. Samples from the same roof have similar dry densities, as would be expected from manufacturing consistency. The dry densities of the XPS boards from the 2016 study ranged from 26 to 43 kg/m^3 for the entire sampling. Of the 15 XPS samples from the 2016 study, the samples from the 11-year-old roof represented both the minimum and the maximum moisture contents by volume, 0.03% and 74%, respectively. By comparison, samples from the 2017 study were observed to range from near dry to 35% MC by volume on the same roof area.

Between the 2016 and 2017 studies, ~30% of samples had moisture contents greater than 30% by volume. Seven of the 13 roof area samples produced XPS insulation boards with both near-dry and wet XPS insulation, ~0.4% and 32–36% by volume, respectively. These results indicate that site-specific exposure conditions may have more impact on the thermal performance of XPS insulation than the number of years in service when considering moisture accumulation in XPS insulation boards.

Overall, various samples had moisture contents higher than would be considered acceptable by today's energy standards due to their reduced thermal performance values. These results indicate that different roof assembly exposure conditions should be more carefully studied in order to understand the variables resulting in moisture accumulation in closed-cell XPS insulation. The data results of the 2016 and 2017 studies will be retained for comparison in an ongoing study by BCIT and RJC continuing the analysis of samples obtained from in-service and to-be-replaced roofing assemblies as further research into the moisture absorption rates of XPS insulation.

Figure 9 shows the average weight distribution from the 2017 samples. It can be observed that the distribution of weight appears to occur from the upper to lower portions of the cross section.

Thermal Conductivity

The physical and thermal characteristics for different types of XPS and EPS insulation materials are defined in ASTM C578, *Standard Specification for Rigid, Cellular Polystyrene Thermal Insulation.* Results of the 2016 study indicated that XPS insulations belong to Type VI class (requiring a minimum density of 25 kg/m^3) and Type VII class (requiring a minimum density of 35 kg/m^3). Based on ASTM C578, and based on the existing labeling from XPS samples,

Sample Label	Roof Age	Dimensions (mm)			Volume (mm³)	Weights (g)		Dry density (kg/m³)	Moisture content by volume
		Length	Width	Thickness		Wet	Oven Dry		(% of dry density)
Samples from 2016 Study									
11-01	11	100	32	38	122770	94.4	3.13	26	30
11-02	11	99	29	36	103852	3.32	3.29	32	1
11-03	11	102	30	35	105839	35.0	3.08	29	11
11-04	11	100	29	37	108005	41.2	2.90	27	14
22-01	22	103	38	38	148112	57.9	4.73	32	12
22-02	22	101	38	37	142660	54.8	4.65	33	12
22-03	22	102	38	37	143808	53.7	4.76	33	11
27-01	27	102	38	36	140805	39.8	5.81	41	7
27-02	27	102	37	37	139810	40.8	5.73	41	7
27-03	27	101	38	37	140392	16.4	5.80	41	3
30-01	30	102	101	36	369051	137.0	15.5	42	9
30-02	30	103	104	37	394432	156.9	16.5	42	10
30-03	30	101	100	37	377024	136.9	16.1	43	9
30-04	30	101	101	36	366323	162.1	15.5	42	10
30-05	30	101	101	37	383625	177.2	16.6	43	11

Table 4 – Sample moisture contents.

Sample Label	Roof Age	Dimensions (mm)			Volume (mm^3)	Weights (g)		Dry density (kg/m^3) *Average values from 2017 Study, drying ongoing	Moisture content by volume
		Length	Width	Thickness		Wet	Oven Dry		(% of dry density)
Samples from 2017 Study									
1130WP - Drain	37	299	299	52	4621417	1598	N/A	24	32
1130WP - Field		297	298	51	4497959	1586	N/A	24	33
1130WP - Upturn		298	298	52	4616534	752	N/A	24	14
777D - Drain	28	302	304	51	4672223	285	N/A	32	3
777D - Field		300	302	52	4689241	608	N/A	32	10
777D - Upturn		301	301	51	4598002	452	N/A	32	7
THQ - Drain	32	300	301	50	4477674	160	N/A	32	0
THQ - Field		300	301	52	4712513	160	N/A	32	0
THQ - Upturn		301	302	52	4676739	1791	N/A	32	35
885WG - Drain	32	301	303	49	4428861	172	N/A	*30	0
885WG - Field		301	299	49	4443644	178	N/A	*30	0
885WG - Upturn		304	303	51	4691578	161	N/A	*30	0
1100M - Drain	38	298	298	51	4549284	285	N/A	*30	3
1100M - Field		303	302	53	4831844	608	N/A	*30	9
1100M - Upturn		305	305	52	4849394	452	N/A	*30	6
WHI - Drain	30+	301	302	53	4772760	127	N/A	*30	0
WHI - Field		301	302	53	4767772	129	N/A	*30	0
WHI - Upturn		301	302	52	4728229	390	N/A	*30	5
RC - Drain	30+	301	301	50	4519427	514	N/A	*30	8
RC - Field		302	301	51	4630206	582	N/A	*30	9
RC - Upturn		302	302	51	4683256	617	N/A	*30	10
FN - Drain	30+	301	302	103	9297746	582	N/A	*30	3
FN - Field		298	299	102	9104617	514	N/A	*30	2
FN - Upturn		305	306	102	9519405	617	N/A	*30	3
ENA - Upturn		301	302	76	6884208	2879	N/A	34	38

Table 5 – Sample moisture contents.

the majority of sampled roofing insulation belong to Type IV class (requiring a minimum density of 32 kg/m^3).

Although these XPS types have different densities, their nominal dry thermal conductivity values are generally around 0.0288 W/(m.K). In this section, this thermal conductivity is used as a reference for comparison with the sample thermal conductivity values, allowing for insight into the degree of deviation from the dry thermal conductivity value. In general, it would be more accurate to have original samples for comparison, but these are not available for a long-term in-service field study. The thermal conductivity and thermal resistance measurement results of the 2016 study and average values from the 2017 study samples are presented in *Table 6* and *Table 7* respectively.

Overall, the thermal conductivity values of field samples from the 2016 study varied from 0.0295 to 0.1752 W/(m.K), which corresponds to between 1.02 and 6.07 times the ASTM reference thermal conductivity value. The thermal conductivity values from the ongoing study varied from 0.0307 to 0.1147 W/(m.K), corresponding to between 1.07 and 3.98 times the ASTM reference thermal conductivity value. Between the 2016 and ongoing studies, 19 of 38 (50%) samples retained over 80% of their expected thermal resistance value, and 13 of 38 (34%) samples had thermal resistance values less than half the value specified in the ASTM standard. From the 2016 study, the highest and the lowest thermal resistance retention, 94% and 16%, respectively, were obtained from a single roof area. Results from the ongoing study observed similar conditions with ranges between 34% and 94% from a single roof area.

Sample ID	Roof Age (Years)	Thickness (mm)	Thermal Conductivity (W/(m.K))	Thermal Resistance (m2.K/W)	Thermal Conductivity ratio (K_sample/K_ref)	Thermal Resistance ratio (TRR) (R_sample/R_ref)
Samples from 2016 Study						
11-01	11	39	0.1752	0.219	6.07	0.16
11-02	11	37	0.0295	1.22	1.02	0.94
11-03	11	37	0.056	0.741	1.94	0.57
11-04	11	38	0.053	0.732	1.84	0.55
22-01	22	37	0.0702	0.528	2.43	0.41
22-02	22	37	0.0669	0.447	2.32	0.35
22-03	22	34	0.0633	0.536	2.19	0.45
27-01	27	38	0.0556	0.68	1.93	0.51
27-02	27	38	0.0629	0.605	2.18	0.45
27-03	27	38	0.0323	1.177	1.12	0.89
30-01	30	39	0.0864	0.446	2.99	0.33
30-02	30	38	0.0948	0.402	3.28	0.3
30-03	30	39	0.0782	0.492	2.71	0.36

Table 6 – Thermal conductivity measurement results of 2016 field samples.

Figure 10 is a graph outlining the thermal resistance ratio (TRR) and the corresponding % moisture content by volume for each sample. The thermal resistance ratio indicates the percentage decrease of thermal resistance of a sample from the reference (dry) thermal resistance value (as described in Tobiasson, 1991).

In general, and as shown in the other referenced works, the thermal resistance decreases with increase in moisture content. The 27- and 30-year sample data lie close to a curve based on *Equations 1* and *2* below, which were developed by Tobiasson et al. (1991) through a series of combined vapor-diffusion-based wetting and thermal-resistance measurements taken from XPS samples in a controlled laboratory setting. In the equations, 'MC' is moisture content by mass in percent.

$$TRR = 100 - 0.12 \times MC \quad \text{for } MC \leq 84\%$$

Equation 1

$$TRR = 137.37e^{(-0.0008 \times MC)} - 39.47 \quad \text{for } MC > 84\%$$

Equation 2

The trend curve in Figure 9 shows that the sampled XPS boards generally have relatively better thermal performance than the trends indicated by the results of the study by Tobiasson et al. (1991). Based on the criteria developed by Tobiasson et al. (1991), 19 of the 41 samples could be deemed to have retained their insulating characteristics. The other samples' thermal resistance reduction values are below the acceptable threshold of 80% of the standard thermal performance. Overall, the variations in thermal performance between samples of similar moisture content may be related to moisture distribution within the samples.

Figure 10 shows the thermal conductivity and the corresponding moisture content measurements of the 2016 and 2017 samples. The thermal conductivities of the XPS samples were found to increase with moisture content and show a similar linear trend as generally determined by other researchers. Based on a laboratory experiment, Dechow and Epstein (1978) provided the following empirical equation for the relationship between thermal conductivity and moisture contents of XPS board (see Equation 3):

$$K_{wet} = 0.0288 + 0.00115 * V$$

K_{wet} is the estimated thermal conductivity of wet insulation in W/m·K;

V is the % moisture content by volume.

Equation 3

Based on Equation 3, sets of thermal conductivity values are calculated for different moisture contents and superimposed on the measured data for comparison purposes. As shown, the trend line based on *Equation 3* and shown in *Figure 11*, developed by Dechow and Epstein, passes through the measured data at low and medium moisture contents, but underestimates the conductivity in the high moisture content in samples above 30% moisture content by volume. As such, this equation provides an estimated thermal conductivity for samples below 30% moisture content by volume but becomes unreliable at higher moisture contents. The sample size from the 2016 and ongoing study does not provide sufficient data for conclusive statements about the thermal performance of XPS insulations at higher moisture contents, but as the ongoing study continues, further conclusions may be reached.

CONCLUSIONS

This work relates obtained closed-cell insulation sample data to the in-service thermal performance at varying moisture contents. Through the results of this study, the performance characteristics of different roof assemblies were compared. Using these roof design comparisons, future roofing designs may avoid conditions that result in moisture accumulation in the insulation component of

Sample ID	Roof Age (Years)	Thickness (mm)	Thermal Conductivity (W/(m.K))	Thermal Resistance (m2.K/W)	Thermal Conductivity ratio (K_sample/K_ref)	Thermal Resistance ratio (TRR) (R_sample/R_ref)
Samples from 2017 Study						
1130WP - Drain	37	52	0.10	0.53	3.37	0.30
1130WP - Field	37	51	0.06	0.87	2.04	0.49
1130WP - Upturn	37	52	0.04	1.21	1.49	0.67
777D - Drain	28	51	0.03	1.47	1.20	0.83
777D - Field	28	52	0.06	0.91	1.97	0.51
777D - Upturn	28	51	0.03	1.56	1.13	0.89
THQ - Drain	32	50	0.03	1.59	1.09	0.92
THQ - Field	32	52	0.03	1.66	1.09	0.91
THQ - Upturn	32	52	0.08	0.61	2.93	0.34
885WG - Drain	32	49	0.04	1.14	1.48	0.67
885WG - Field	32	49	0.04	1.31	1.31	0.76
885WG - Upturn	32	51	0.03	1.49	1.19	0.84
1100M - Drain	38	51	0.03	1.66	1.07	0.94
1100M - Field	38	53	0.03	1.51	1.21	0.83
1100M - Upturn	38	52	0.04	1.46	1.24	0.81
WHI - Drain	*30+	53	0.03	1.66	1.10	0.91
WHI - Field	*30+	53	0.03	1.65	1.11	0.90
WHI - Upturn	*30+	52	0.03	1.69	1.07	0.93
RC - Drain	*30+	50	0.03	1.47	1.18	0.85
RC - Field	*30+	51	0.03	1.55	1.14	0.87
RC - Upturn	*30+	51	0.03	1.59	1.12	0.89
FN - Drain	*30+	103	0.03	3.22	1.11	0.90
FN - Field	*30+	102	0.03	3.24	1.09	0.92
FN - Upturn	*30+	102	0.03	3.15	1.12	0.89
ENA - Upturn	*30+	76	0.11	0.66	3.98	0.25

*Actual age to be confirmed during ongoing study.

Table 7 – Thermal conductivity measurement results of 2017 field samples.

the roof assembly. For example, the installation of vapor relief layers recommended by Kunzel and Kiesl, 1997, appears to be consistent with these results, while the mechanism for moisture absorption remains to be determined. Some specific conclusions from this study are:

- XPS insulation samples retrieved from all sites showed a measurable increase in density due to moisture absorption.
  - — The increase in mass may be of concern for the structural design of roof assemblies.
  - — The increase in weight for the wetter samples indicates potential load increases up to 1.0 kPa (20 psf).
  - — The density of wet XPS roof insulation samples could be a concern depending on the structural limits of the assembly.
- The thermal performance characteristics of the wet insulations had significantly degraded as a result of moisture absorption.
- The moisture contents of samples differed on the same roofing site; future studies should include the local exposure conditions and specific sample locations, and note surrounding conditions/roof features.
- The sample with the highest moisture content also had the shortest exposure time (2016 study assembly with 11 years in service), indicating that exposure conditions and roofing design may be significant factors.
- Sectional images of prepared samples show upper surface damage and deterioration (cracking) allow moisture deeper into the samples. Damages appear to be associated with point loads from aggregate ballast, drainage mat, or paver pedestals indenting and/or penetrating the surface of the XPS. Cracking

characteristics of samples are similar to those of freeze–thaw damage solid materials.

- The moisture content of XPS tends to be higher in assemblies with continuous layers above, including pavers or concrete slabs on a continuous layer of sand acting as a leveling material.
- As roofing design standards (RCABC, 2016; Smith, 2014) recommend drainage layers above and below the XPS layers, a comparison of similar assemblies incorporating various combinations of drainage layers above and below the XPS layers should be explored.
- The majority of the moisture accumulation appears to occur in the upper exterior surface of the insulation. This may be the result of various conditions, including the condensation point of the cross section, moisture remaining on the upper surface of the insulation, or damage being introduced to the upper surface of the insulation.

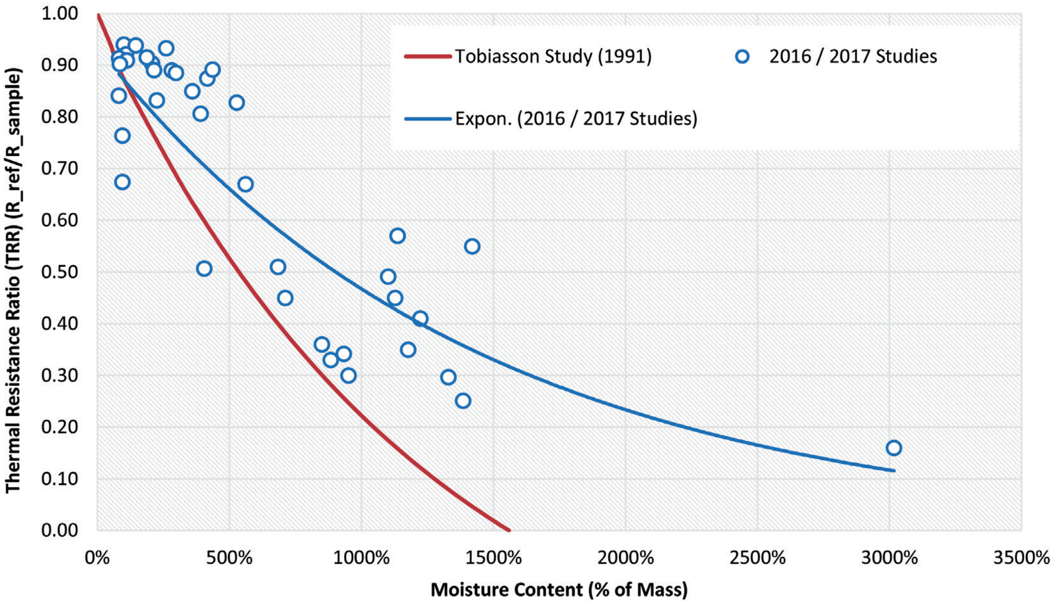


Figure 10 – Thermal resistance ratio (TRR) and % MC relationship for 2016 and ongoing study XPS samples.

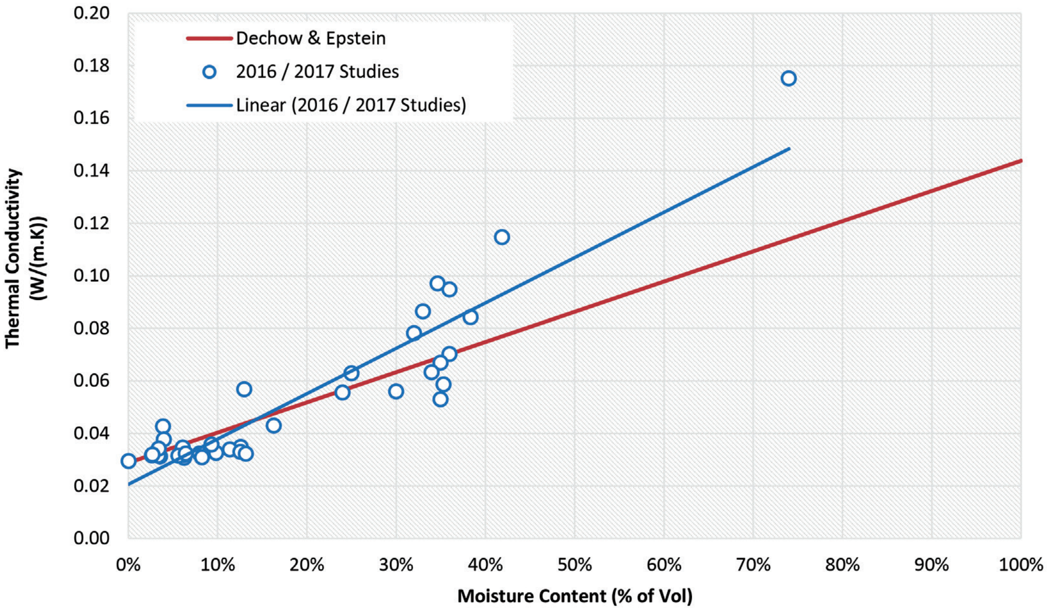


Figure 11 – Thermal conductivity of XPS samples as a function of moisture contents.

RECOMMENDED ADDITIONAL STUDY

The limited sample size of the 2016 and 2017 studies indicates that further sampling is required to provide proper conclusions on the thermal performance of XPS insulation at higher moisture contents. The results from an ongoing study would identify roofing assembly design practices that result in moisture accumulation in the insulation and that could be avoided in future design. As the ongoing study continues to develop, it will provide further insight into exposure condition variables such as weather history, roof features such as overhangs, etc., and assembly variations such as drainage layers, ballast type, and layer continuity. Ongoing improvements to the roofing assembly design are required in order to meet the long-term durability requirements of thermal layers when exposed to inclement weather and site-specific climate conditions.

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