THERMAL RESISTANCE OF EXTRUDED EXPANDED POLYSTYRENE (XEPS): FIELD DATA FROM WESTERN CANADA

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ABSTRACT

Extruded expanded polystyrene (XEPS) insulation has been installed in protected roofing membrane (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 BC, XEPS samples were found to have ranges of water accumulation from low to high moisture contents after a range of years in service. The data includes wet and dry densities as well as the measured heat transfer coefficients of samples obtained from existing PMR assemblies. The data indicates that closed cell insulations like XEPS in plaza, parkade, and roofing PMRs may absorb moisture over their service life 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. This 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 life.

INTRODUCTION

The protected membrane roofing (PMR) assembly is designed to protect the waterproofing membrane from exposure to weather related thermal stresses, UV radiation, and mechanical damage (RCABC, 2016, Smith, T. 2014). PMR systems are commonly used for low-slope waterproofing, plaza waterproofing, and vegatative roofing assemblies. The assembly consists of a waterproofing membrane below layers of insulation and ballast that may consist of aggregate, concrete, pavers, or soil for vegatative roofing. Ballast and insulation layers may be combined to form products like concrete or mortar faced XEPS panels. The placement of the insulation layers is designed maintain the waterproofing membrane at a temperature closer to that of the interior and increase the membrane's life expectancy (Dechow *et al*. 1978 , Basham, D.L. et. al. 1999). Basham stated that certain closed cell insulations are suitable in a wet environment above the roof membrane and that such roofs can provide energy conservation by providing a continuous thermal barrier exterior to the thermal mass of the structure.

XEPS has been installed in PMRs for about 45 years and is currently a standard product for exposed insulation assemblies purposes. In some waterproofing applications XEPS insulation is exposed to conditions that result in moisture accumulation while in service. Previous research includes laboratory and field performance measurements of insulation behaviour in exposure to exterior environments (Dechow *et al*. 1978, Sandberg, P.I. 1986, Tobiansson *et al.* 1991, Kunzel and Kiesl, K., 1997, Crandell. 2010). Through calculation of results with measurement support, Kunzel and Kiesl found that moisture performance of XEPS depends on the mean relative humidity (RH) at the

upper surface of the insulation. The results determined that exposure of XEPS 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 10 years on many insulation types and concluded that XEPS had the best thermal performance due to its resistance to water absorption. They noted that XEPS insulation's thermal resistance would be reduced as it absorbed water, and that XEPS should be expected to maintain at least 80% of its thermal resistance for a 10-year period to be considered non-deficient. In a building energy–saving study, Kehrer. *et al.* 2012 retrieved field samples from foundation walls after 15 years and determined that moisture accumulation in XEPS had an influence on the long term energy performance of the waterproofing assembly. They also concluded that XEPS and Etruded 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 XEPS should be considered as a factor in the durability of the waterproofing assembly's thermal performance.

Field observations of waterproofing assemblies have established that components of the waterproofing below the ballast may remain damp or wet while in service, and that the weight of the insulation layer increases as it absorbs water. As engineering design relies upon expected values for thermal conductance and material densities, assessment of the wetting conditions and associated degradation of thermal resistance values and increased loading of the structure due to water accumulation warrants further study. This preliminary study presents data on the measured physical properties of insulation samples retrieved from PMRs, with years in service ranging from 11 to 38 years. Measured properties include wet weights and thermal resistance values from an ongoing study on the thermal performance and distribution of moisture through XEPS samples from in-service waterproofing assemblies. Additional measured properties include the wet and dry weights from the results of a 2016 Study by L. Peer, Fitsum et. al., of a similar nature. The main objectives of these studies were to correlate relationships between existing waterproofing assemblies and the measured properties of XEPS samples from the assemblies including moisture accumulation and thermal conductivity. To achieve these objectives, the following tests were conducted on XEPS samples obtained from in-service waterproofing assemblies:

1) Thermal conductivity measurement: Using a heat flow meter (HFM), measure the thermal conductivity of XEPS insulation samples obtained from in-service waterproofing assemblies,

2) Moisture Content (MC) of field samples (2016 Study): determine amount of water absorbed by the XEPS samples while in service. The moisture content and thermal conductivity data are used to develop a relationship between the results.

3) Samples obtained following the 2016 study do not include the dry weights of the samples XEPS insulations as it is a preliminary work and part of an ongoing study. An estimate of the MC values was determined using the average dry densities from the 2016 study. MC values will be updated as the ongoing study is finalized in 2018.

Table 1 Properties of various XPS insulation Types from ASTM C578-17A

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·ft²·h/Btu (K·m²/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·m²)	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/ft³ (kg/m³)	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)

TEST SAMPLES

Test samples were retrieved from in-service waterproofing assemblies or during waterproofing replacement projects from 2015 - 2017 in Western Canada (Figure 1). Samples sites were provided randomly based on their availability during assessment services or as provided voluntarily by waterproofing replacement Contracting companies. Table 2 below describes the service conditions for each sample set.

Table 2: Description of field insulation samples retrieved for testing

Site Location	Installation Date	Years in Service	Assembly	Assembly details	Roof Area
Calgary	**2003**	**11**	**Exterior Pedestrian Plaza**	***50mm pavers, 25mm Sand, 50 mm insulation (XEPS), Membrane, concrete 0% slope***	**N/A**
Vancouver	**1993**	**22**	**Protected Membrane Roofing**	***70mm precast concrete paver, filter fabric, 38mm insulation (XEPS) [*24.8kg/m³], liquid applied urethane membrane, structural decking with 2% slope***	**N/A**
Vancouver	**1988**	**27**	**Roof top parking at Mall**	***100 mm cast-in-place (CIP) concrete, 38mm insulation (XEPS), 1.6mm rubberized asphalt/polyethylene waterproofing membrane, concrete deck with 1.5% slope***	**50**
Burnaby	**1985**	**30**	**5th Floor covered parking garage**	***90mm CIP Concrete, 38mm insulation (XEPS), EPDM Membrane, concrete deck with 2% slope***	**25**
Vancouver	**1980**	**37**	**Penthouse Roof Deck**	***Bricks on bedding sand, filter fabric, 50mm insulation (XEPS) [*32kg/m³], 2-ply SBS Mod. Bit membrane***	**400**

Vancouver	**1989**	**28**	**Recreational plaza over mall**	***Pavers on neoprene pedestals, filter fabric, 50mm insulation (XEPS) [**32kg/m^3], rubberized asphalt HDPE membrane***	**3500**
Burnaby	**1985**	**32**	**Protected Membrane Roofing**	***Gravel ballast, 50mm insulation (XEPS), Polyethylene slipsheet, 3-ply built-up roofing membrane with with asphalt flood coat, concrete structure***	**1440**
Burnaby	**1985**	**32**	**Protected Membrane Roofing**	***Concrete Slab, 50mm insulation (XEPS), Polyethylene slipsheet, 3-ply built-up roofing membrane with asphalt flood coat, concrete structure***	**1440**
Vancouver	**1985**	**32**	**Protected Membrane Roofing**	***Aggregate ballast, filter fabric, 50mm insulation (XEPS), rubberized asphalt HDPE membrane***	**320**
Vancouver	**1979**	**38**	**Protected Membrane Roofing**	***Aggregate ballast, filter fabric, insulation (XEPS) [**32kg/m^3], polyethylene slip sheet, rubberized asphalt HDPE membrane***	**156**
Victoria	***???**	**30+**	**Protected Membrane Roofing**	***Aggregate ballast, filter fabric, 50mm insulation (XEPS) [**32kg/m^3], waterproofing membrane***	**312**
UBC	***???**	**30+**	**Protected Membrane Roofing**	***Aggregate ballast, 50mm insulation (XEPS, built-up roofing (BUR) Membrane***	**336**
UBC	***???**	**30+**	**Protected Membrane Roof Deck**	***50mm precast concrete pavers on pedestals, 100mm insulation (XEPS), 2-ply SBS mod. bit membrane***	**45**
U of C	***???**	**30+**	**Protected Membrane Roofing**	***50mm precast concrete pavers, 75mm insulation (XEPS), TPO membrane***	**750**

*Actual age to be confirmed during ongoing study.

**Densities based on manufacturer's 2017 product data sheets.

The samples were taken from typical construction projects with a variety of exposure conditions, for instance:

- Two waterproofing assemblies with aggregate ballast,
- One waterproofing assembly with 2" continuous concrete pavers on pedestals,
- One waterproofing assembly with a continuous concrete slab,
- One waterproofing assembly with bedding sand and brick pavers,
- No waterproofing assemblies with built-in drainage layers,
- Three waterproofing assemblies with 0.5 – 2% slope.

The samples had similar construction 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 year round

The 'roof area sampled' column indicates the waterproofing area in square meters from which the samples were obtained. Samples from larger areas were generally father apart when sampled, and may have been exposed to more varied site conditions. Conditions include exposure to sun or shade, drainage performance due to proximity of drains and organic build-up, continuity and vapour permeability of ballast layers, see Figure 1 for example sampling conditions.

Figure 1: Samples retrieved from a High Rise Penthouse Roof

EXPERIMENTAL SETUP

Sample Preparation

Samples of insulation removed from the waterproofing assemblies in BC were wrapped in 3mil 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 site in BC were weighed within 48 hours of procurement. Shipping times for samples from outside of BC took up to 3 days. Test samples for thermal conductivity and moisture content measurements were prepared from each XEPS board as shown in **Error! Reference source not found.**. A total of 52 samples for moisture content and thermal conductivity measurement were prepared from 13 insulation boards for the 2016 study. To date, a total of 579 samples have been prepared from 67 XEPS sample insulation boards obtained from site for moisture content and thermal conductivity measurement for the ongoing study. The 300mm by 300mm 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 weight as well as their length, width, and thickness were measured. The timeline between samples being removed from site and sample preparation varied from hours to several days depending on the site location and heat flow meter availability.

Figure 2: Thermal conductivity and moisture content measurement sample preparation

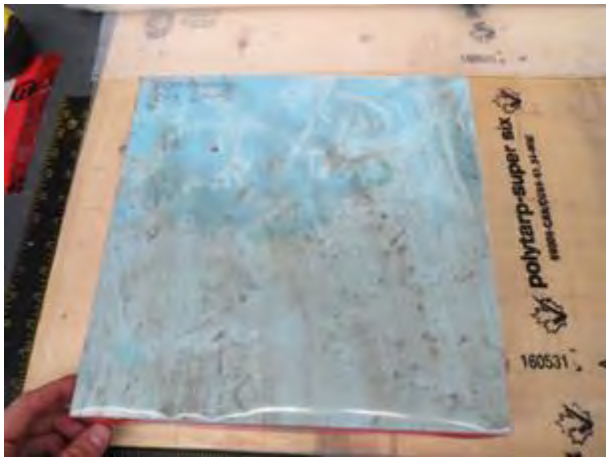

Figure 3: Thermal conductivity test samples wrapped with 6-mil polyethylene film and sealed with tape to avoid moisture loss

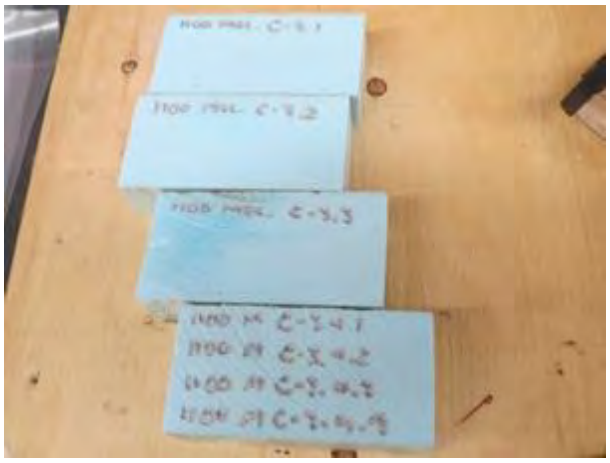

Figure 4: Three moisture content and 1 moisture distribution measurement samples

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 XEPS 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 some pressure, **Error! Reference source not found.**. The samples were not stored beneath the water table, so the pressure is thought to be due to trapped air within the sample.

Figure 5: Freshly cut cross-section of insulation from the ongoing study, showing strong directional absorption from surface and cracks and flaws in the foam material

Moisture Content Measurement

The moisture contents of the 2016 Samples were determined by gravimetric means using a Veritas Analytical Balance, accurate to 0.0001 g, and a forced air convective oven, Figure 6. After taking the initial weights of the samples, they were placed in the oven and left to dry at 70°C. Every 24 hours the samples were taken out of the oven, weighed and put back into the oven for further drying till the samples are declared 'dry'. The samples were assumed to be at dry state when three successive weight measurements were within 0.1% 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 time constraints and the drying requirements for heavier samples, the dry weights of the ongoing study samples have not been determined. In order to provide an estimate for MC of the ongoing study sample's dry weights, the average dry density from the 2016 Samples was used. It should also be noted that the majority of XEPS samples obtained were Type IV, with a density of 32kg/m3 as indicated on the product data sheet. The ongoing study will obtain the dry weights of samples over the coming year and moisture content data will be finalized for 2018.

Moisture Contents are reported in this paper mostly as % by volume of the sample porosity. Even though the moisture contents were assessed by mass, other papers generally converted the measurements to % by volume during discussions for various reasons. Some reasons include that the dry densities of insulations vary, so the mass % gain over the initial mass would not have allowed for comparisons between results. Additionally, the high measured moisture contents relative to the low dry densities result in % mass valus in the thousands of percentages at relatively low MC values, which are difficult to relate to a physical reality. The % 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.

Figure 6: a) Scale for measuring masses of samples and b) Convection oven with drying samples.

Thermal Conductivity

The thermal conductivity of the 300 mm long x 300 mm wide test samples was measured using a Netzsch 436 Lambda Heat Flow Meter. According to the manufacturer's specification, the heat flow meters have an accuracy of ±1% and repeatability ±0.3%. The measurements were carried out in accordance with ASTM C518 – 10, at mean temperature of 24°C and temperature difference of 20°C. The test set-up temperatures are listed in Table 2.

Table 2: Testing set-up of Temperature and accuracy

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 set-up for steady-state conditions

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	%

Prior to testing, the heat flow meter was calibrated at the test temperature conditions using a standard reference material (SRM 1450C432). The thermal conductivity 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 300mm x 300mm samples from each sample location were used in the ongoing study to determine the average thermal conductivity value at each location.

RESULTS

Moisture Content

In the same roof of a building, moisture contents in the insulation boards appear to differ significantly from location to location. This is apparently due to varying micro-climate conditions or waterproofing details over their years in service. For example, the weights of samples from an 11 year-old assembly ranged from 141.36 grams to 2,496.27 grams as shown in Figure 7, 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 1,791 grams as shown in Table 3, a weight ratio of approximately 11.2 between the samples.

Figure 5: Weights of two samples from the 2016 study

The moisture contents of exposed insulation samples, along with their corresponding oven dry weights (2016 Study), are presented in Table 3. The moisture content values in Table 3 represent resulting measurements from the 2016 study. The samples' 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 XEPS boards from the 2016 study ranged from 26 - 43 kg/m3 between different waterproofing sites. Of the fifteen XEPS 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. Using the average dry density from the 2016 study, similar conditions were observed where a single high rise roof assembly produced samples of estimated moisture contents ranging from near dry to 35% MC by volume.

Between the two studies, ~30% of samples had moisture contents greater than 30% by volume. 7 of the 13 roof areas samples produced XEPS insulation boards with both near-dry and wet XEPS 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 XEPS insulation than the number of years in service when considering moisture accumulation in XEPS insulation boards.

Overall, a significant portion of the samples had moisture contents higher than would be considered normal, and their thermal values are significantly degraded as a result. These results are also significantly higher than reported in previous papers. These results indicate that exposure conditions and absorption properties need to be more carefully studied in order to predict water absorption rates into closed cell exstruded polystyrene insulation, so that assemblies can maintain their thermal performance for the duration of the expected service life. These results will be included as part of an ongoing study that will includes samples taken from a minimum of 30 waterproofing assemblies with emphasis on targeted waterproofing features including drainage bodies, vertical upturn detailing (parapet, base of wall, etc.), and in the field of the waterproofing assembly for further research into the moisture absorption rates of XEPS insulation.

Table 3: Measured Properties of XEPS samples from 2016 and Ongoing Study

Sample Label	Roof Age	Dimensions (mm)			Volume (mm³)	Weights (g)		Dry density (kg/m³)	Moisture content by volume (% of dry density)	Moisture content by volume (% of Vol)	Assembly Description
		Length	Width	Thickness		Wet	Oven Dry				
Samples from 2016 Study											
11-01	**11**	**100**	**32**	**38**	**122770**	**94.4**	**3.13**	**26**	**30**	**74**	**50mm precast concrete pavers**
11-02	**11**	**99**	**29**	**36**	**103852**	**3.32**	**3.29**	**32**	**1**	**0.03**	**50mm precast concrete pavers**
11-03	**11**	**102**	**30**	**35**	**105839**	**35.0**	**3.08**	**29**	**11**	**30**	**50mm precast concrete pavers**
11-04	**11**	**100**	**29**	**37**	**108005**	**41.2**	**2.90**	**27**	**14**	**35**	**50mm precast concrete pavers**
22-01	**22**	**103**	**38**	**38**	**148112**	**57.9**	**4.73**	**32**	**12**	**36**	**70mm concrete brick paver, 2% Slope**
22-02	**22**	**101**	**38**	**37**	**142660**	**54.8**	**4.65**	**33**	**12**	**35**	**70mm concrete brick paver, 2% Slope**
22-03	**22**	**102**	**38**	**37**	**143808**	**53.7**	**4.76**	**33**	**11**	**34**	**70mm concrete brick paver, 2% Slope**
27-01	**27**	**102**	**38**	**36**	**140805**	**39.8**	**5.81**	**41**	**7**	**24**	**100 mm CIP concrete, 1.5% slope**
27-02	**27**	**102**	**37**	**37**	**139810**	**40.8**	**5.73**	**41**	**7**	**25**	**101 mm CIP concrete, 1.5% slope**
27-03	**27**	**101**	**38**	**37**	**140392**	**16.4**	**5.80**	**41**	**3**	**8**	**102 mm CIP concrete, 1.5% slope**
30-01	**30**	**102**	**101**	**36**	**369051**	**137.0**	**15.5**	**42**	**9**	**33**	**90mm CIP Concrete, 2% slope**
30-02	**30**	**103**	**104**	**37**	**394432**	**156.9**	**16.5**	**42**	**10**	**36**	**90mm CIP Concrete, 2% slope**
30-03	**30**	**101**	**100**	**37**	**377024**	**136.9**	**16.1**	**43**	**9**	**32**	**90mm CIP Concrete, 2% slope**
30-04	**30**	**101**	**101**	**36**	**366323**	**162.1**	**15.5**	**42**	**10**	**0.4**	**90mm CIP Concrete, 2% slope**
30-05	**30**	**101**	**101**	**37**	**383625**	**177.2**	**16.6**	**43**	**11**	**0.4**	**90mm CIP Concrete, 2% slope**
Samples from Ongoing Study											
1130WP - Drain		**299**	**299**	**52**	**4621417**	**1598**	**N/A**	**36**	**9**	**31**	**Interlocking brick pavers on bedding sand**
1130WP - Field	**37**	**297**	**298**	**51**	**4497959**	**1586**	**N/A**	**36**	**10**	**32**	**Interlocking brick pavers on bedding sand**
1130WP - Upturn		**298**	**298**	**52**	**4616534**	**752**	**N/A**	**36**	**4**	**13**	**Interlocking brick pavers on bedding sand**
777D - Drain	**28**	**302**	**304**	**51**	**4672223**	**285**	**N/A**	**36**	**2**	**2**	**Pavers on pedestals, 2% slope**
777D - Field		**300**	**302**	**52**	**4689241**	**608**	**N/A**	**36**	**4**	**9**	**Pavers on pedestals, 2% slope**

777D - Upturn		**301**	**301**	**51**	**4598002**	**452**	**N/A**	**36**	**3**	**6**	**Pavers on pedestals, 2% slope**
THQ - Drain		**300**	**301**	**50**	**4477674**	**160**	**N/A**	**36**	**1**	**0**	**Aggregate ballast**
THQ - Field	**32**	**300**	**301**	**52**	**4712513**	**160**	**N/A**	**36**	**1**	**0**	**Aggregate ballast**
THQ - Upturn		**301**	**302**	**52**	**4676739**	**1791**	**N/A**	**36**	**11**	**35**	**Concrete slab**
885WG - Drain		**301**	**303**	**49**	**4428861**	**172**	**N/A**	**36**	**1**	**0**	**Aggregate ballast**
885WG - Field	**32**	**301**	**299**	**49**	**4443644**	**178**	**N/A**	**36**	**1**	**0**	**Aggregate ballast**
885WG - Upturn		**304**	**303**	**51**	**4691578**	**161**	**N/A**	**36**	**1**	**0**	**Aggregate ballast**
1100M - Drain		**298**	**298**	**51**	**4549284**	**285**	**N/A**	**36**	**2**	**3**	**Aggregate ballast**
1100M - Field	**38**	**303**	**302**	**53**	**4831844**	**608**	**N/A**	**36**	**3**	**9**	**Aggregate ballast**
1100M - Upturn		**305**	**305**	**52**	**4849394**	**452**	**N/A**	**36**	**3**	**6**	**Aggregate ballast**
WHI - Drain		**301**	**302**	**53**	**4772760**	**127**	**N/A**	**36**	**1**	**0**	**Aggregate ballast**
WHI - Field	**30+**	**301**	**302**	**53**	**4767772**	**129**	**N/A**	**36**	**1**	**0**	**Aggregate ballast**
WHI - Upturn		**301**	**302**	**52**	**4728229**	**390**	**N/A**	**36**	**2**	**5**	**Aggregate ballast**
RC - Drain		**301**	**301**	**50**	**4519427**	**514**	**N/A**	**36**	**3**	**8**	**Aggregate ballast**
RC - Field	**30+**	**302**	**301**	**51**	**4630206**	**582**	**N/A**	**36**	**3**	**9**	**Aggregate ballast**
RC - Upturn		**302**	**302**	**51**	**4683256**	**617**	**N/A**	**36**	**4**	**10**	**Aggregate ballast**
FN - Drain		**301**	**302**	**103**	**9297746**	**582**	**N/A**	**36**	**2**	**3**	**50mm precast concrete pavers on pedestals**
FN - Field	**30+**	**298**	**299**	**102**	**9104617**	**514**	**N/A**	**36**	**2**	**2**	**50mm precast concrete pavers on pedestals**
FN - Upturn		**305**	**306**	**102**	**9519405**	**617**	**N/A**	**36**	**2**	**3**	**50mm precast concrete pavers on pedestals**
ENA - Upturn		**301**	**302**	**76**	**6884208**	**2879**	**N/A**	**36**	**11**	**38**	**50mm precast concrete pavers**

*Actual age to be confirmed during ongoing study.

Thermal Conductivity

The physical and thermal characteristics for different types of XEPS and EPS (Expanded Polystyrene) insulation materials are defined in ASTM C578, "Standard Specification for Rigid, Cellular Polystyrene Thermal Insulation". Results of the 2016 study indicated that XEPS insulations belong to Type VI Class (requiring a minimum density of 25 kg/m3) and Type VII Class (requiring a minimum density of 35 kg/m3). Based on ASTM C578, and based on the existing labeling from XEPS samples, the majority of sampled roofing insulation belong to Type IV Class (requiring a minimum density of 32 kg/m3). Although these XEPS types have different densities, their nominal dry thermal conductivity values are similar at 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 25 XEPS samples collected for the ongoing study are presented in Table 4.

Table 4: Thermal conductivity measurement results of 2016 and ongoing study

Sample ID	Roof Age (Years)	Thickness (mm)	Dry density (kg/m3)	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	26	0.1752	0.219	6.07	0.16
11-02	11	37	32	0.0295	1.22	1.02	0.94
11-03	11	37	29	0.056	0.741	1.94	0.57
11-04	11	38	27	0.053	0.732	1.84	0.55
22-01	22	37	32	0.0702	0.528	2.43	0.41
22-02	22	37	33	0.0669	0.447	2.32	0.35
22-03	22	34	33	0.0633	0.536	2.19	0.45
27-01	27	38	41	0.0556	0.68	1.93	0.51
27-02	27	38	41	0.0629	0.605	2.18	0.45
27-03	27	38	41	0.0323	1.177	1.12	0.89
30-01	30	39	42	0.0864	0.446	2.99	0.33
30-02	30	38	42	0.0948	0.402	3.28	0.3
30-03	30	39	43	0.0782	0.492	2.71	0.36
Samples from Ongoing Study							
1130WP - Drain	37	52	32	0.10	0.53	3.37	0.30
1130WP - Field	37	51	32	0.06	0.87	2.04	0.49

1130WP - Upturn	37	52	32	0.04	1.21	1.49	0.67
777D - Drain	28	51	32	0.03	1.47	1.20	0.83
777D - Field	28	52	32	0.06	0.91	1.97	0.51
777D - Upturn	28	51	32	0.03	1.56	1.13	0.89
THQ - Drain	32	50	32	0.03	1.59	1.09	0.92
THQ - Field	32	52	32	0.03	1.66	1.09	0.91
THQ - Upturn	32	52	32	0.08	0.61	2.93	0.34
885WG - Drain	32	49	32	0.04	1.14	1.48	0.67
885WG - Field	32	49	32	0.04	1.31	1.31	0.76
885WG - Upturn	32	51	32	0.03	1.49	1.19	0.84
1100M - Drain	38	51	32	0.03	1.66	1.07	0.94
1100M - Field	38	53	32	0.03	1.51	1.21	0.83
1100M - Upturn	38	52	32	0.04	1.46	1.24	0.81
WHI - Drain	*30+	53	32	0.03	1.66	1.10	0.91
WHI - Field	*30+	53	32	0.03	1.65	1.11	0.90
WHI - Upturn	*30+	52	32	0.03	1.69	1.07	0.93
RC - Drain	*30+	50	32	0.03	1.47	1.18	0.85
RC - Field	*30+	51	32	0.03	1.55	1.14	0.87
RC - Upturn	*30+	51	32	0.03	1.59	1.12	0.89
FN - Drain	*30+	103	32	0.03	3.22	1.11	0.90
FN - Field	*30+	102	32	0.03	3.24	1.09	0.92
FN - Upturn	*30+	102	32	0.03	3.15	1.12	0.89
ENA - Upturn	*30+	76	32	0.11	0.66	3.98	0.25

*Actual age to be confirmed during ongoing study.

Overall, the thermal conductivity values of field samples vary 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 samples retained over 80% of their expected thermal resistance value, 13 of 38 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.

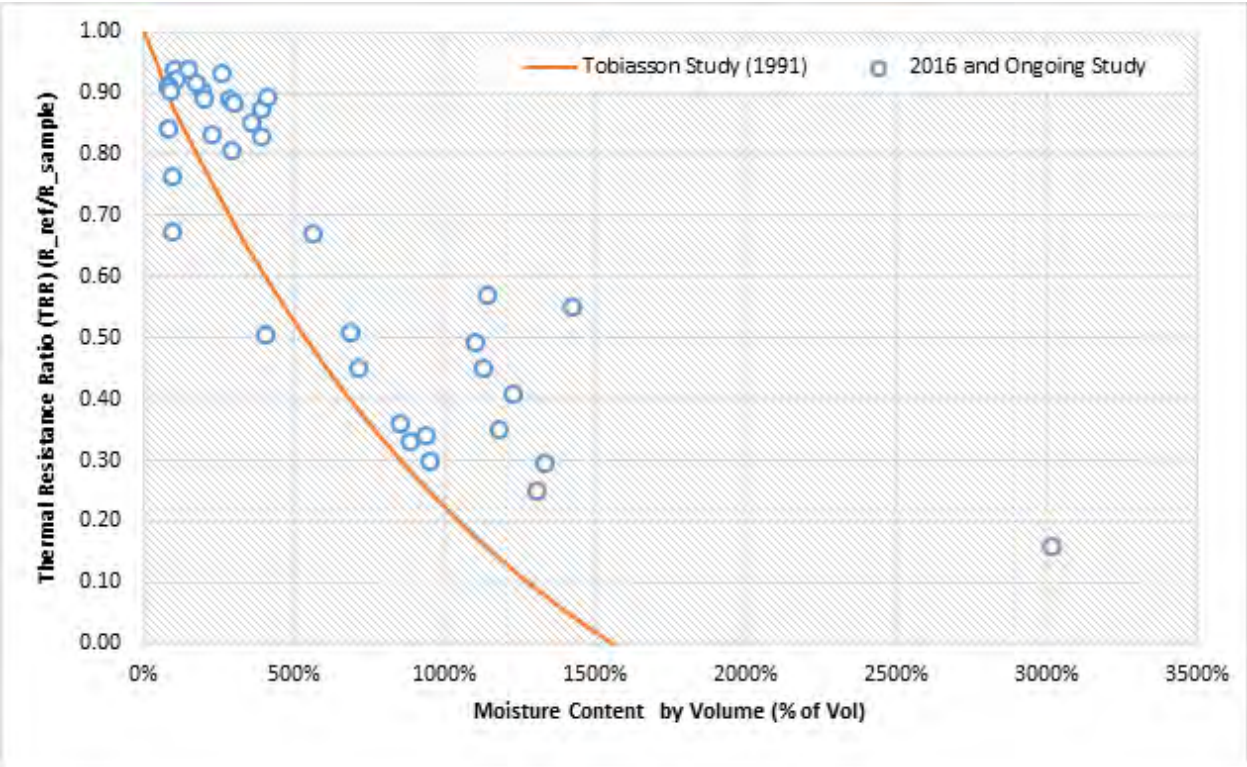

Figure 6: Thermal resistance ratio (TRR) and % MC relationship for 2016 and Ongoing Study XEPS samples

Figure 6 graphs 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 *et al*). In general, and as has been shown in the other referenced works, as the moisture content increases, the thermal resistance decreases. The 27 and 30 year sample data lie close to a curve based on Equation (1) and (2), which were developed by Tobiansson et al. (1991) through series of combined vapor diffusion based wetting and thermal resistance measurements taken from XEPS samples in a controlled laboratory setting. In the equations 'MC' is moisture content by mass in percent.

$$TRR = 100 - 0.12 \times MC \quad for\ MC \leq 84\% \tag{1}$$

$$TRR = 137.37e^{(-0.0008 \times MC)} - 39.47 \quad for\ MC > 84\% \tag{2}$$

The trend curve in Figure 8 shows that the XEPS boards sampled generally have relatively better thermal performance than the trends indicated by the results of the study by Tobiansson et al. (1991). Based on the criteria developed by Tobiansson et al. (1991), nineteen 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 9 below shows the thermal conductivity and the corresponding moisture content measurements of the samples from the four roofs. The thermal conductivity of the XEPS 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 XEPS board:

$$K_{wet} = 0.0288 + 0.00115 * V \tag{3}$$

K_{wet} is the estimated thermal conductivity of wet insulation in W/m·K;
V is the % moisture content by volume.

Based on Equation (3), sets of thermal conductivity values are calculated for different moisture contents and superimposed on the measured data in Figure 9 for comparison purposes. As shown, the trend line based on the equation 3, 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 to date do not provide sufficient data for conclusive statements about the thermal performance of XEPS insulations at higher moisture contents but as the ongoing study continues further conclusions may be reached.

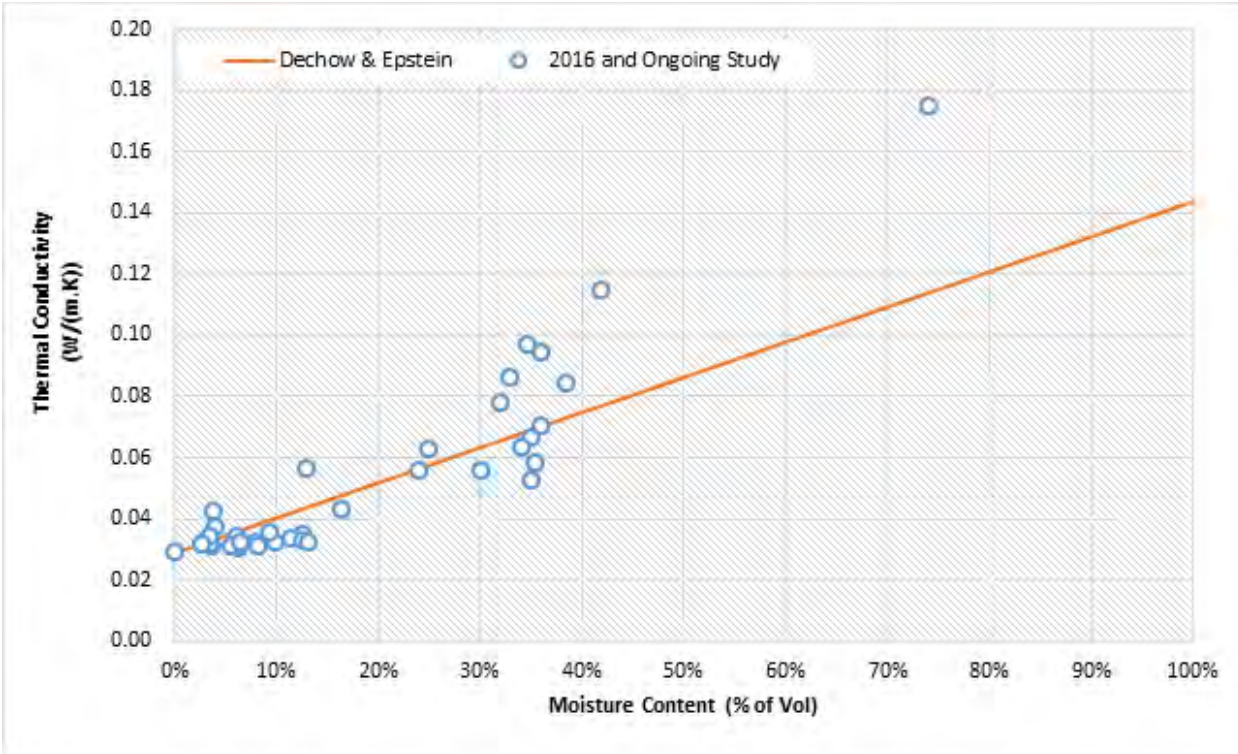

Figure 7: Thermal conductivity of XEPS samples as a function of moisture contents

CONCLUSIONS

This work relates field observations made with respect to absorption of water by closed cell insulation, and through testing establishes the need for further study of XEPS insulation in exposed waterproofing assemblies to allow for durable design in future waterproofing assemblies. Installation of vapour relief layers recommended by Kunzel and Kiesl 1997 and Dow appear to be important and their effectiveness at higher %MC values needs to be verified. Some specific conclusions from this study are:

- XEPS 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 limits of the roof assemblies. For example, the increase in weight for a 100mm XEPS at the 74% MC by volume observed during sampling would indicate potential load increases of up to 740Pa (15 psf).

- 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 waterproofing site, indicating that the local exposure conditons and waterproofing design should be considered when interpreting the results.

- The sample with highest moisture content and shortest exposure time was from the 2016 study assembly with 11 years in service, further indicating that exposure conditions and waterproofing design should be considered

- Images of sample cross sections indicate that upper surface damage in combination with freeze-thaw action may have been a factor in moisture absorption. Damages appears to be associated with point loads from aggregate ballast, drainage mat, or paver pedestals penetrating indenting the XEPS.

- The moisture contents of XEPS tend to be higher in assemblies with continuous layers above including pavers on a continuous layer of bedding sand or CIP concrete slabs. As roofing design standards recommend drainage layers above and below the XEPS layers, a comparison of similar assemblies incorporating various combination of drainage layers above and below the XEPS layers should be explored.

The limited sample size of the ongoing study to date indicates that further sampling is required to provide proper conclusions on the thermal performance of XEPS insulation at higher moisture contents. The results of the ongoing study will allow for further improvements to waterproofing assembly design in regards to thermal performance durability over the expected service life. As the ongoing study continues to develop, it will provide further insight into exposure condition variables such as weather history, roof features like overhangs, etc. as well as assembly variations like drainage layers, and ballast type and continuity. Ongoing improvements to the waterproofing 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.

REFERENCES

RCABC (2016). Roofing Practices Manual (RPM Online). Roofing Contractors Association of British Columbia. 9734 201 street, Lanley, BC, Canada.

http://rpm.rcabc.org/index.php?title=3.13_PROTECTED_MEMBRANE_AND_MODIFIED_PROTECTED_MEMBRANE_ROOFING_SYSTEMS

Smith, T. et. al. (2014). Building Envelope Design Guide – Roofing Systems. Whole Building Design Guide (WBDG), a program of the National Insttitute of Building Science. 1090 Vermont Avenue NW, Suite 700, Washington, DC, USA. https://www.wbdg.org/design/env_roofing.php

Basham, D.L. et. Al. (1999). Commentary on Roofing Systems. Technical Instructions. US Army Corps of Engineers, Engineering Division, Directorat of Military Programs, Washington, DC, 20314-1000.

Sandberg, P. I. (1986). "Moisture content and thermal conductivity in soil insulation." Journal of Thermal Insulation, volume (10), pp. 124-141.

Dechow, F.J. and Epstein, K.A. (1978), Laboratory and field investigations of moisture absorption and its effect on thermal performance of various insulations. Thermal Transmission Measurements of insulations, Special Technical Publication (STP) 600, American Society for Testing and Materials (ASTM), pp. 234 – 260.

Tobiasson, W. and Ricard, J. (1979). Moisture Gain and Its Thermal Consequence for Common Roof Insulations:"Proceedings of 5th conference on Roofing Technology, National Roofing Contractors

Association, Oak Park, IL.,

Tobiansson, W., Greaiorex, A. and Van Pelt, D. (1991). New wetting curves for common roof insulations. International Symposium on Rooting Technology. Pp 383-390

Kunzel H. M., Kiesl, K., (1997) Moisture Behaviour of Protected Membrane Roofs With Greenery. CIB W40 Proceedings Tokyo

Crandell, J. (2010). "Below-Ground Performance of Rigid Polystyrene Foam Insulation: Review of Effective Thermal Resistivity Values Used in ASCE Standard 32-01—Design and Construction of Frost-Protected Shallow Foundations." *J. Cold Reg. Eng.*, 10.1061/(ASCE)CR.1943-5495.0000012, 35-53.

Kehrer. M., Christian, J, (2012). Measurement of Exterior Foundation Insulation to Assess Durability In Energy-Saving Performance. Oak Ridge National Laboratory, Oak Ridge, Tennessee ORNL/TM-2012/159

DOW Building Solutions – Protected Membrane Roof Installation Guidelines (Canada and US) undated

ASTM C1498 Standard (2010). Test Method for Hygroscopic Sorption Isotherms of Building Materials (2010) published by ASTM International, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959

ASTM C518 (2012). Standard Test Method for Steady State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus (2015) published by ASTM International, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959

ASTM C578-17a. (2017) “Standard Specification for Rigid, Cellular Polystyrene Thermal Insulation”; published by ASTM International, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959