# Thermal and Moisture Properties of Extruded Polystyrene (XPS) from Inverted Roofs: A Pilot Study

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ASHRAE TWEEP XIII
December 5, 2016

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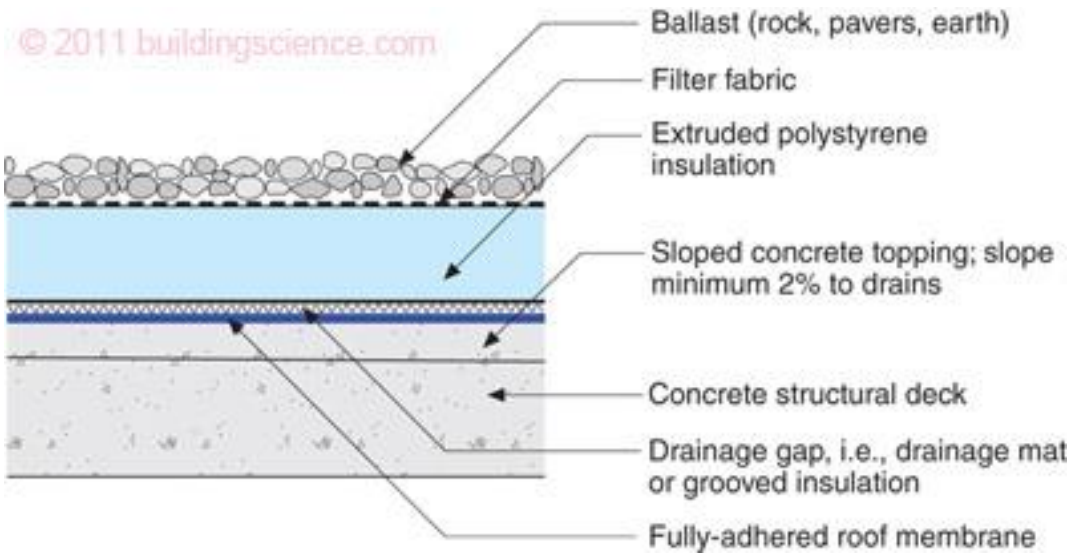
Creative Thinking Practical Results

# Outline

- Introduction
- Test Samples
- Experimental Methods
- Test Results
- Conclusion

# Insulation from Inverted Roof Systems

- Also call Protected Membrane Roof (PMR) system
- Protect roofing and water proofing membrane from exposure to weather stress, thermal stress, UV and mechanical damage
- Cover them with insulation and ballast using gravel, concrete, or pavers.

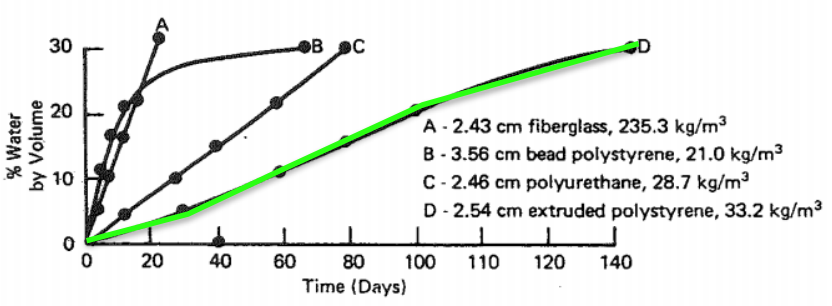


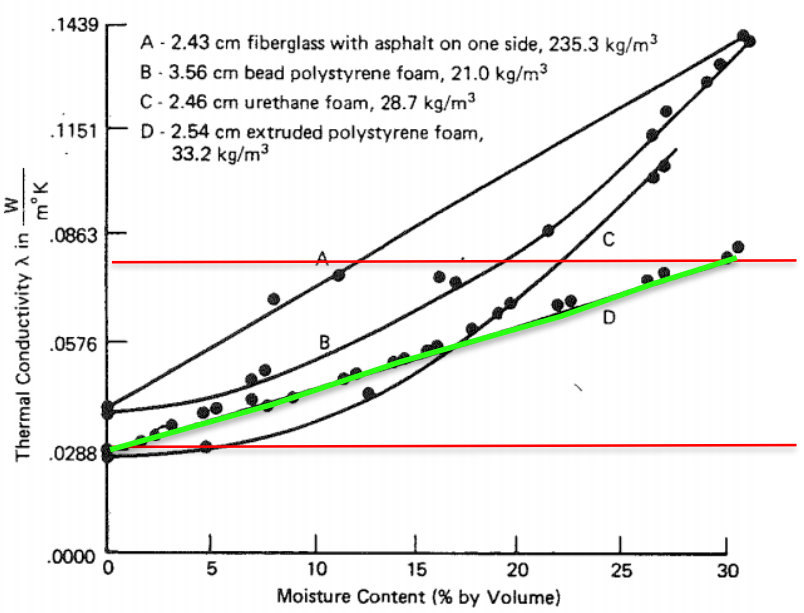

- Used for low-slope roofs
- XPS is common insulation and has been installed in PMR systems for 45 years
  - Due to low water absorption compared with other insulation types.
  - Maximum water absorption 0.3% by volume in 24 hours (ASTM C578)

# Moisture Absorption by Diffusion Experiment (Dechow & Epstein, 1978)

## Boundary Conditions:

- Saturated (100% RH) and 50°C
- Lab Condition 50% RH and 20°C




- Less moisture accumulation compared with other insulation types.
- Thermal conductivity of XPS increases with moisture content
  - Increases by a factor of about 3 at 30% moisture content by volume

# Objectives of this study

- To assess the level of moisture accumulation in XPS insulation from field samples
- Investigate thermal resistance change of the insulation after relatively long field service periods.
- Secondary objective of calculating Vapour Diffusion Coefficients using data from field wetted samples

# Samples Retrieved from Buildings

| Date Constructed | Years in Service | Assembly details | Sample locations |
|---|---|---|---|
| Calgary 2003 | 11 | 50mm pavers<br>25mm Sand<br>38 mm insulation<br>Hot Applied Asphalt Membrane<br>Concrete 0% slope | 4 |
| Nanaimo 1993 | 22 | 70mm concrete brick paver<br>Filter fabric<br>38mm insulation<br>Liquid applied urethane membrane<br>Concrete 2% slope | 3 |
| New Westminster 1988 | 27 | 100 mm CIPconcrete<br>38mm insulation<br>1.6mm SA Asphalt membrane<br>Concrete 1.5% slope | 3 |
| Burnaby 1985 | 30 | 90mm CIP Concrete<br>38mm insulation<br>EPDM Membrane<br>Concrete 2% slope | 5 |

- XPS samples were installed over membranes over heated enclosures under concrete toppings
- The assemblies did not have drainage mats above or beneath the insulation
- All except one had slope to drain

# 11 Years Calgary Constructed 2003

- 0% slope
- 2” Concrete paver and sand bed overburden

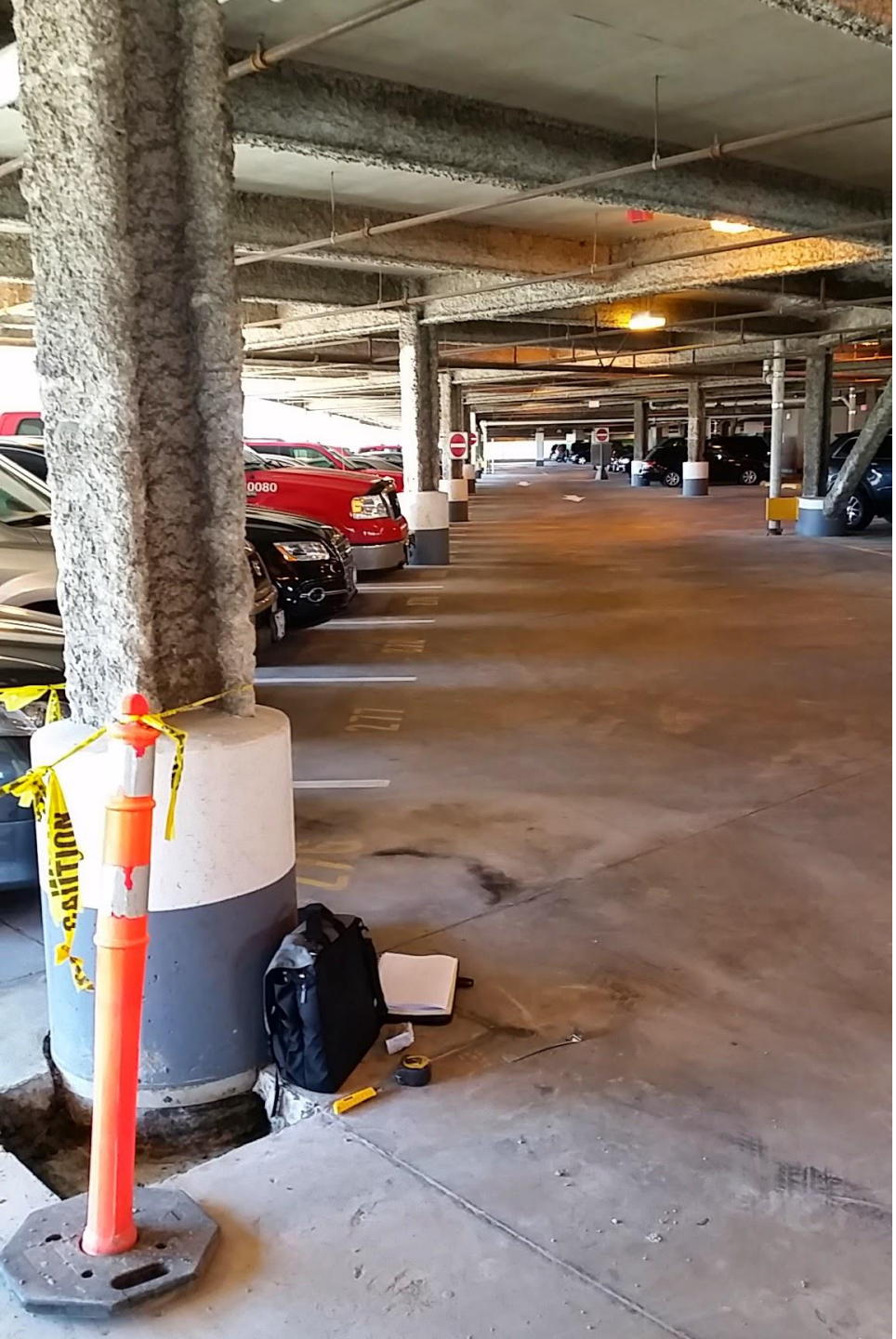
# 22 years old
# Nanaimo
# Constructed 1993

- Roof top patios

  floors 5 to 7
- 2% slope to drain
- 3” concrete pavers over filter fabric

# 27 years
# New Westminster
# Constructed 1988

- 1.5% slope to drain
- 4” concrete topping
- Concrete topping caused membrane to ‘walk’ on the deck

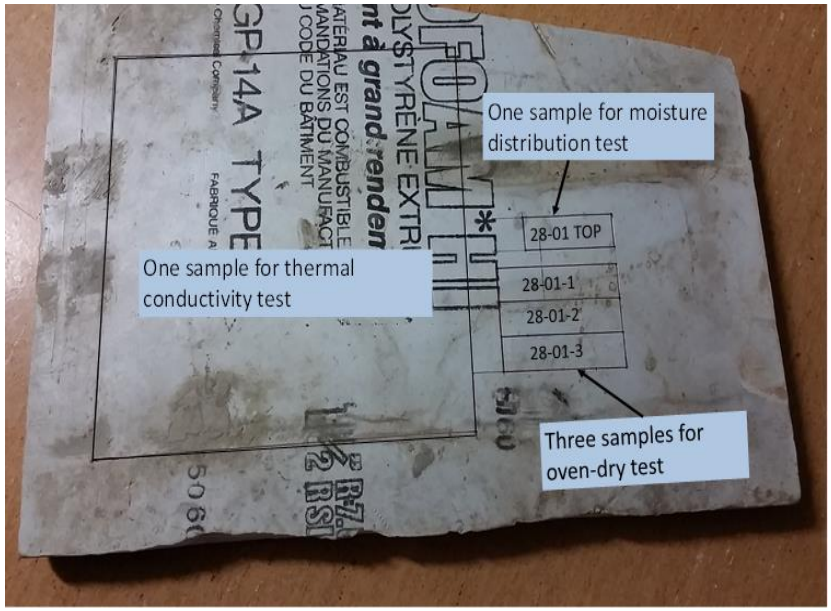


# 30 years old Burnaby Constructed 1985

- 3 ½ inch Concrete topping
- Covered area of parkade
- 2% slope to drain

# Sample Preparation

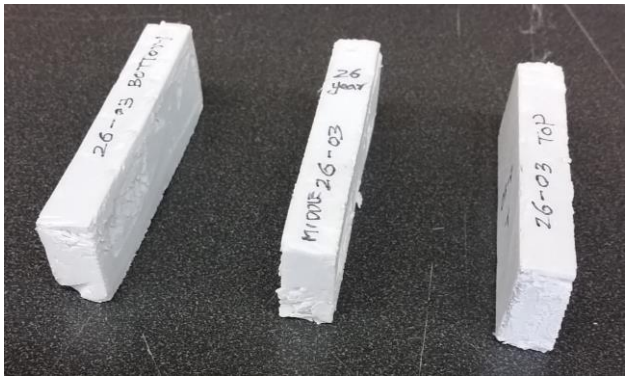
XPS board were separately sealed in plastic or foil and delivered to lab




- 3 Thermal Conductivity samples

- 3 Moisture Content Samples

- 3 Slices Cut Across The Thickness



- Once the samples were cut, their initial weights, dimensions were measured right away
- Thermal conductivity samples were sealed with poly

# Observation

- Water appeared on the fresh-cut lines

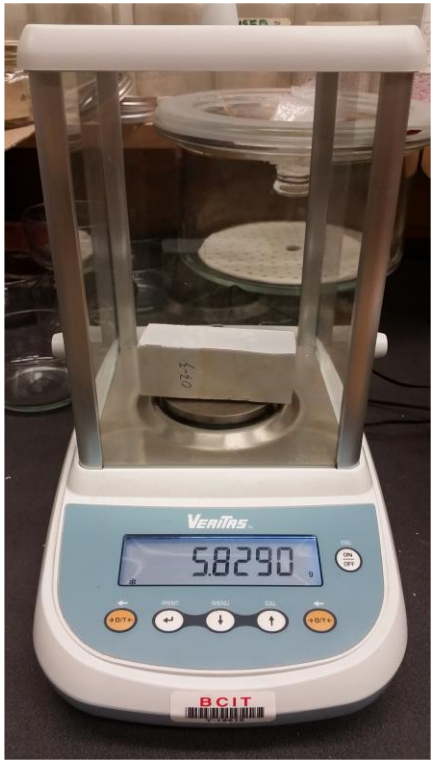
- Water beaded on the cutting surface

- Uneven water distribution through thickness

- Water appeared when slicing the samples
- Water appeared on knife blade when cutting samples

# Moisture Content Measurements

- Moisture contents were determined by gravimetric means
- Dry mass of the samples were determined using convective oven at 70 $^{o}$C, and three successive weight measurements were within 0.1% (ASTM C1498)

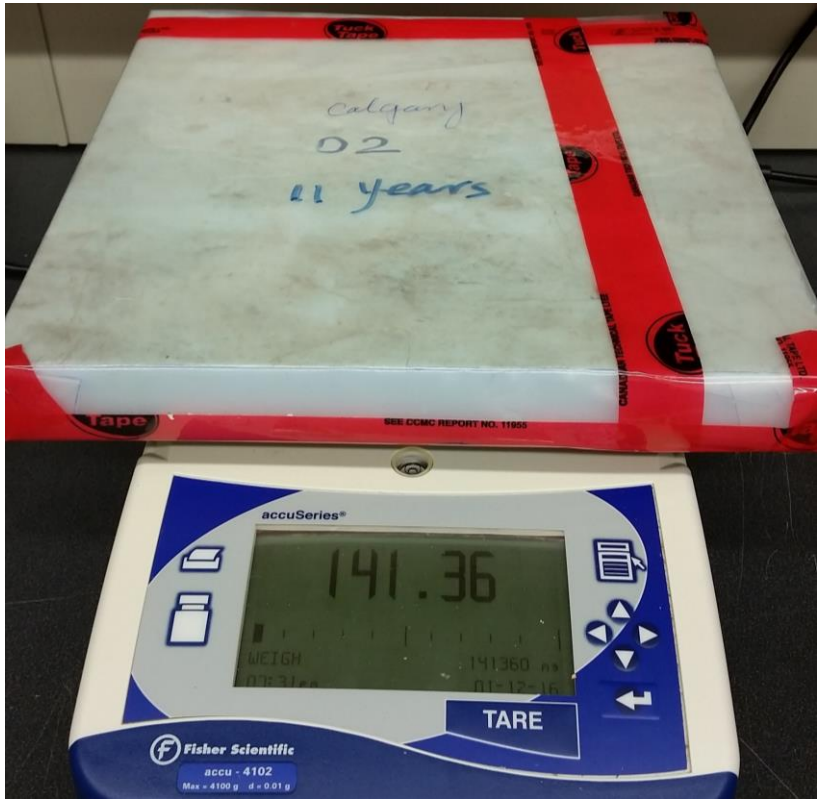



| Sample ID | Dry Density ($kg/m^3$) | MC by Vol ( %) |
|---|---|---|
| 11 - 1 | 26 | 74 |
| 11 - 2 | 32 | 0.03 |
| 11 - 3 | 29 | 30 |
| 11 - 4 | 27 | 35 |
| 22 - 1 | 32 | 36 |
| 22 - 2 | 33 | 35 |
| 22 - 3 | 33 | 34 |
| 27 - 1 | 41 | 24 |
| 27 - 2 | 41 | 25 |
| 27 - 3 | 41 | 8 |
| 30 - 1 | 42 | 33 |
| 30 - 2 | 42 | 36 |
| 30 -3 | 43 | 32 |

# Test Results: Moisture Content

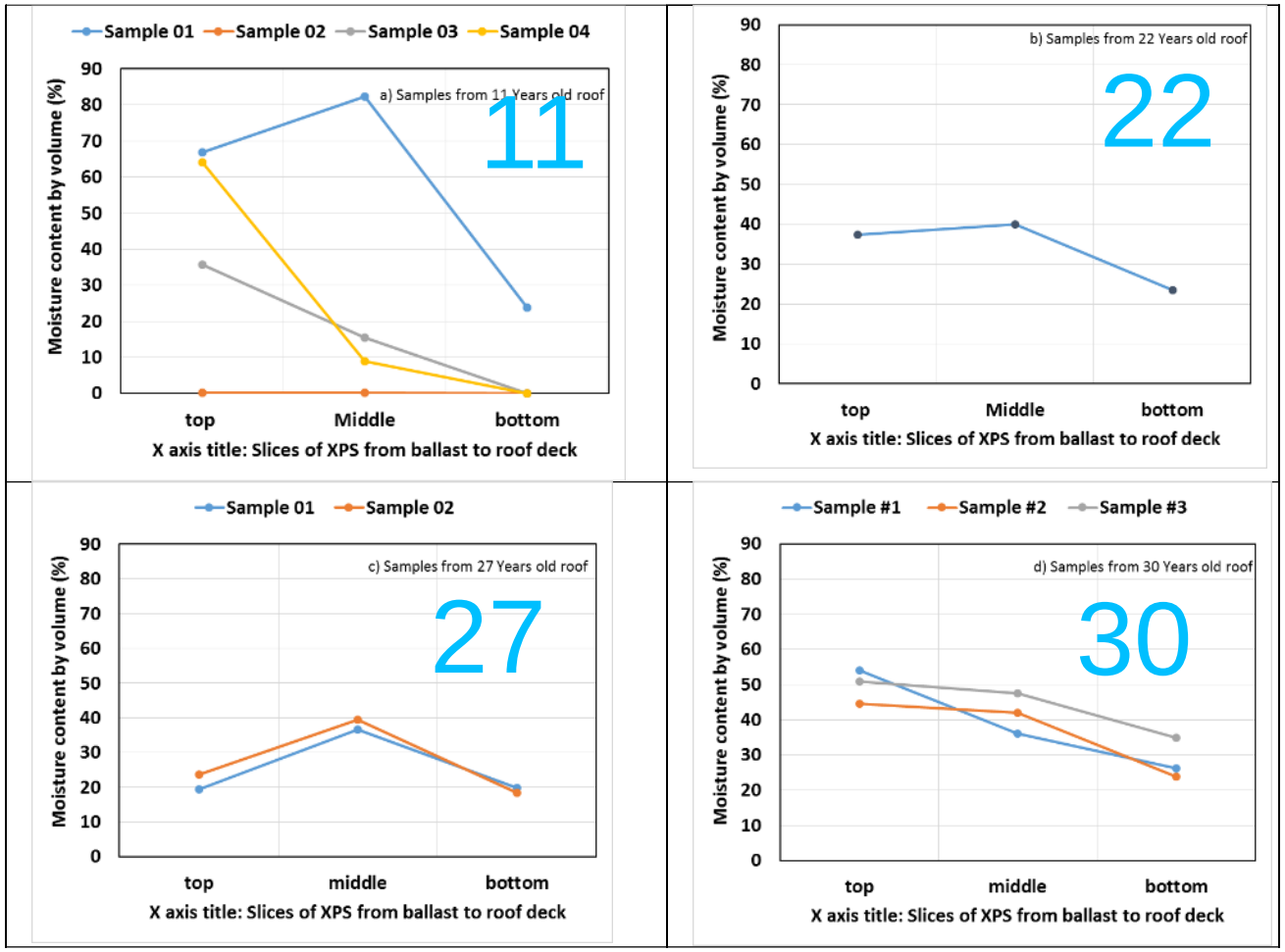
- The samples from the 11 year old roof represented both the maximum and the minimum moisture contents
- About half of the samples had moisture contents between 30 and 36%.

# Water Absorption at Different Locations


- The difference between weights of two samples is 17 times.
- Apparently that local exposure conditions play a big role in moisture accumulation

# Moisture Distribution in XPS Samples




- Moisture content distributions are not uniform
- Generally moisture contents of top layers are high compared to bottom layers.

# Thermal Conductivity Measurement

- Thermal conductivity are measured using a Heat Flow Meter (NETZSCH)
- Measurements are done according to ASTM C518

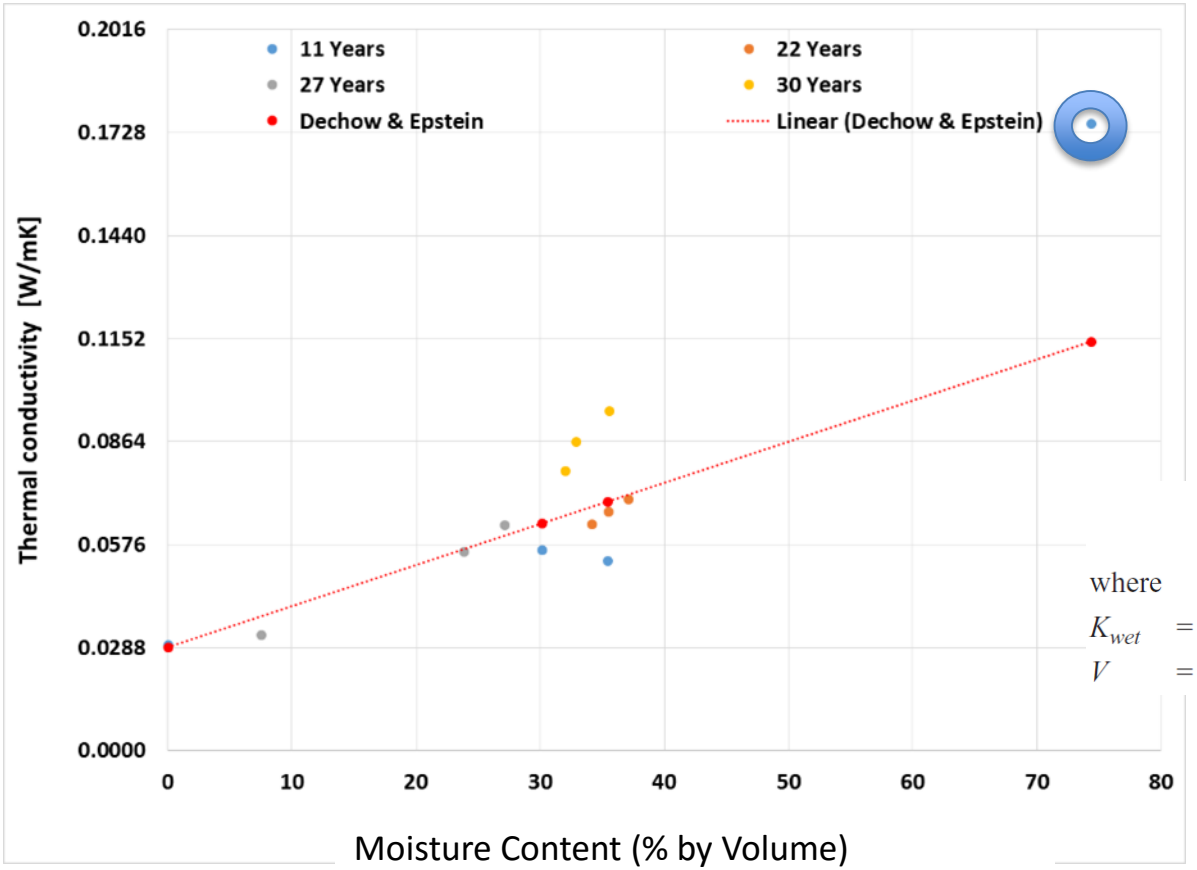

| Test conditions | |
|---|---|
| Mean temperature | 24.0°C |
| Temperature difference | 20.0°C |
| Upper temperature | 34.0°C |
| Lower temperature | 14.0°C |

# Thermal Conductivity Measurement

| Sample ID | MC by Vol ( %) | Thermal Conductivity (W/(m.K)) | Thermal Resistance (m².K/W) | Thermal Conductivity ratio (K_sample/K_ref) | Thermal Resistance ratio (R_sample/R_ref) |
|---|---|---|---|---|---|
| 11-01 | 74 | 0.1752 | 0.219 | 6.07 | 0.16 |
| 11-02 | 0.03 | 0.0295 | 1.220 | 1.02 | 0.94 |
| 11-03 | 30 | 0.0560 | 0.741 | 1.94 | 0.57 |
| 11-04 | 35 | 0.0530 | 0.732 | 1.84 | 0.55 |
| 22-01 | 36 | 0.0702 | 0.528 | 2.43 | 0.41 |
| 22-02 | 35 | 0.0669 | 0.447 | 2.32 | 0.35 |
| 22-03 | 34 | 0.0633 | 0.536 | 2.19 | 0.45 |
| 27-01 | 24 | 0.0556 | 0.680 | 1.93 | 0.51 |
| 27-02 | 25 | 0.0629 | 0.605 | 2.18 | 0.45 |
| 27-03 | 8 | 0.0323 | 1.177 | 1.12 | 0.89 |
| 30-01 | 33 | 0.0864 | 0.446 | 2.99 | 0.33 |
| 30-02 | 36 | 0.0948 | 0.402 | 3.28 | 0.30 |
| 30-03 | 32 | 0.0782 | 0.492 | 2.71 | 0.36 |

- The thermal conductivity values vary from 0.0295 to 0.1752 W/(m.K)
- Which corresponds to between 1 and 6 times the ASTM reference thermal conductivity value.
- Only two samples retained over 80% of their expected thermal resistance value,
- About two-third of the samples' thermal resistance values are less than half the value of reference material
- About one-third of the samples' thermal resistance values are less than 1/3$^{rd}$ the reference materials
- Or in other words are conducting 3x as much heat as standard.

# Thermal Conductivity vs Moisture Content




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

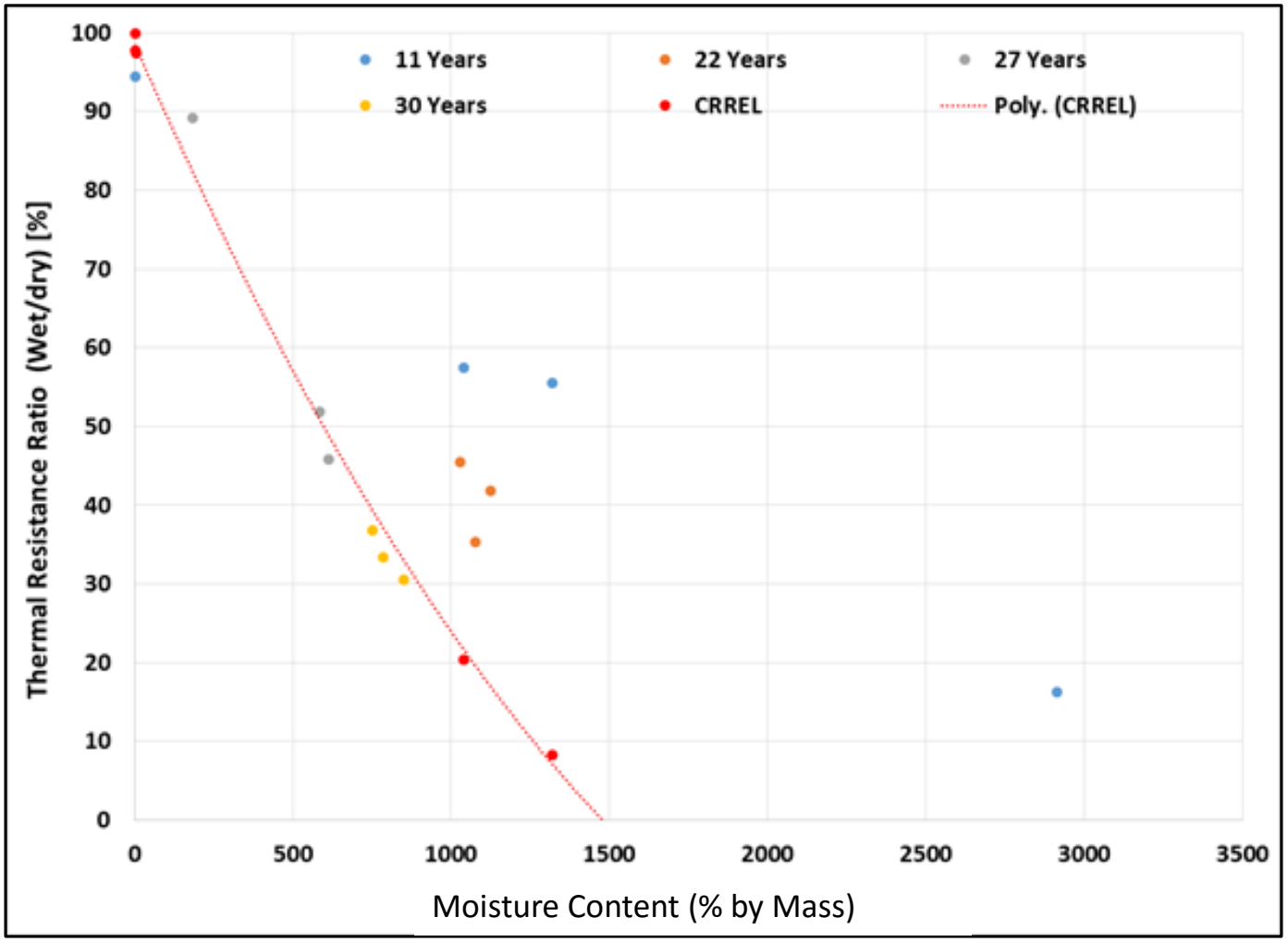
where

$K_{wet}$ = thermal conductivity of wet XPS board, W/m·K

$V$ = moisture content,% by volume

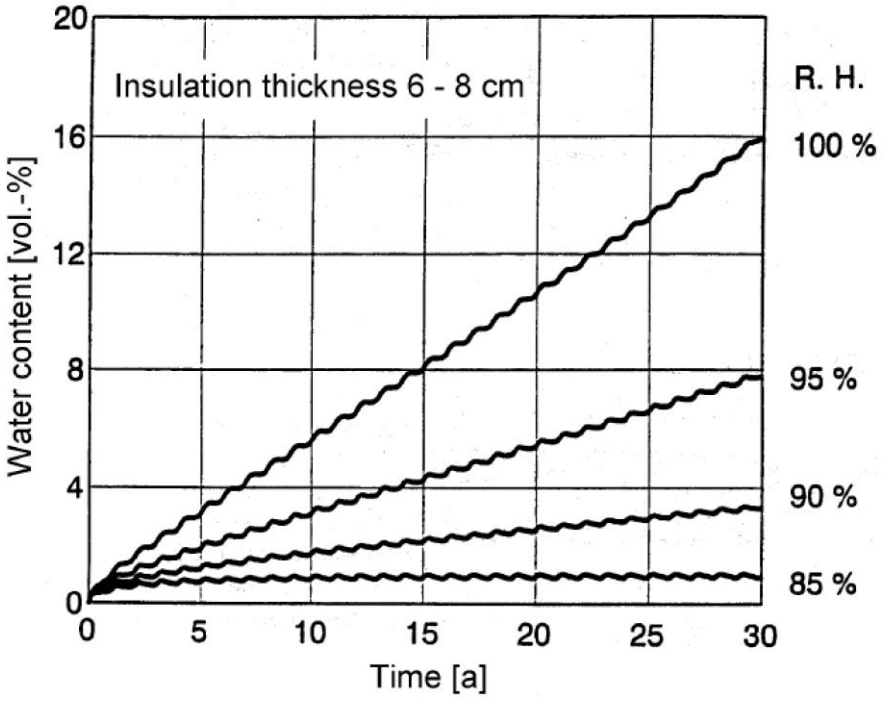
From Dechow and Epstein (1978)

# Thermal Conductivity vs Moisture Content




CRREL:
Tobiansson
*et.al.* (1991)

# Influence of sustained high Relative Humidity levels on rate of moisture accumulation




Kunzel and Kiessl 1997

Fig. 1 Calculated Long-term moisture behaviour of extruded polystyrene insulation slabs in inverted roofs depending on the mean relative humidity in close vicinity of the upper surface of the slabs.

# Conclusions

- Extruded Polystyrene is reported to be the least absorbent polymer insulation, however thermal values of the wet insulation are significantly degraded due to levels of moisture absorbed in service under these unventilated plaza roof assemblies
- Density of the wet insulation increased to levels where it would be a concern for loading of some roof structures.
- Both type VI and Type VII insulations seem to be affected by moisture absorption.
- The sample with highest moisture content and shortest exposure time was from a Calgary roof, possibly implicating freeze thaw as a mechanism in wetting XPS insulation
- Assembly design, characterized by DOW as “Vapour open”, is important for controlling moisture accumulation. The moisture contents differed from location to location on the same roofs, indicating that the local exposure conditions are as important as time in service when it comes to moisture accumulations.
- Degree of ventilation required to reduce Relative Humidity to below 85% is not known for a variety of assemblies. A wider study is underway, with statistically viable numbers of samples, to isolate field variables such as time of wetness, insulation type, frost action, drainage, and vapour relief layers in an attemp to generalize findings.
- Publish vapour induced moisture absorption rates data for XPS insulation

End


## Moisture Absorption

**THE ISSUE**

STYROFOAM™ Brand Extruded Polystyrene Foam Insulation will absorb water and the insulation value will be reduced.

**DISCUSSION**

In a PMR design, it is critical that any insulation installed above the membrane can perform in a wet environment without any detrimental effects on its long-term performance. STYROFOAM™ Brand Extruded Polystyrene Foam Insulation has a unique closed-cell structure that provides excellent moisture resistance and long-term R-value.

Nine PMR systems were monitored over a period of 22 years and the insulation properties assessed. The average moisture content of the insulation was 0.9 percent on a percent by volume basis, with a retained R-value of 96 percent.

In plaza deck designs, it is important that a drainage layer be created above the insulation, allowing precipitation to drain off the top surface of the insulation, creating a "diffusion open" assembly. If the insulation is sandwiched between a vapour barrier (e.g., pavers) and the roof deck, vapour cannot escape so it is driven back into the insulation. To create a "diffusion open" layer, ensure impermeable roof coverings (such as pavers) have a ventilating air space. This could be a layer of fine-free gravel or a 3/16" (5 mm) minimum air space. See "Pavers" on page 12 for additional details. In addition, if the wearing surface is installed in direct contact with the insulation, moisture may become trapped and freeze-thaw cycling could cause spalling on the bottom of the wearing surface.

Always ensure that the roof deck has proper drainage; if the PMR system has significant ponding (e.g., standing water), the insulation will not be "diffusion open." Follow roofing association guidelines for drainage recommendations.

**CONCLUSION**

STYROFOAM™ Brand Extruded Polystyrene Foam Insulation offers demonstrated long-term performance in a PMR assembly

# PMR with Membrane below the Insulation

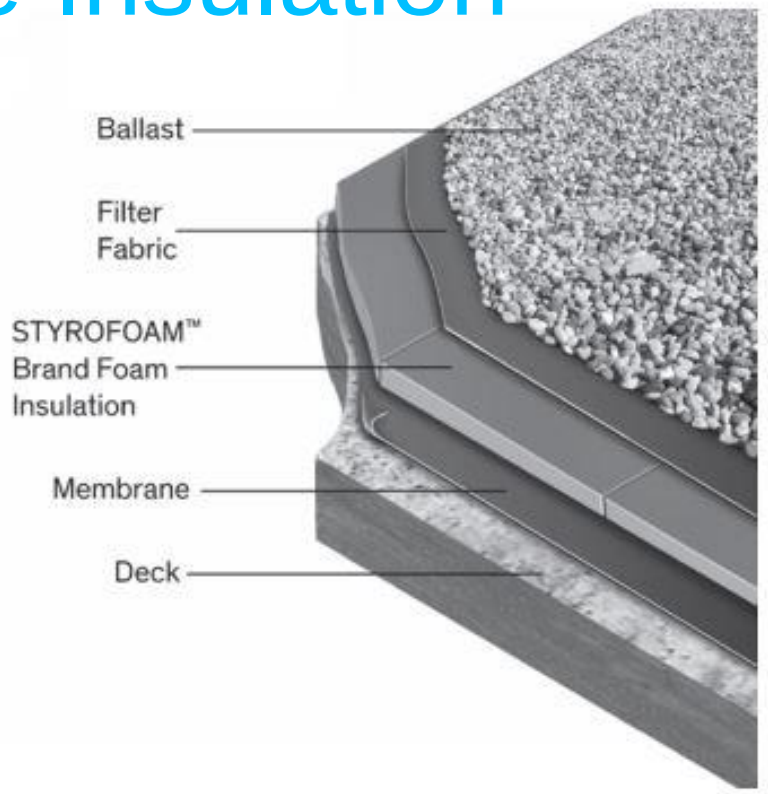



FIGURE 2: PMR With Membrane Below the Insulation

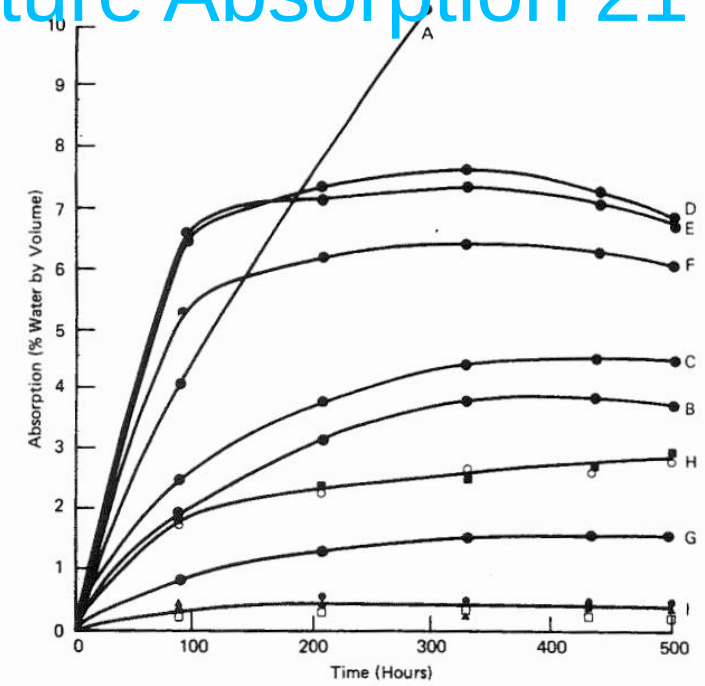
# Test Samples – ASTM & manufacture expectation

- Only 0.3% Water absorption rate by volume in 24hrs (ASTM C272 in C578)
- 1.1 – 1.5 perm for 1.0 inch XPS permeance
- maintain 80% thermal resistance (ASCE 32-01)
- Remarkably durable and water-resistant and can have multiple “lives”, which means XPS can be reused.

| Type (Per ASTM C578) | Unit | XPS for 1 in. (25.4 mm) thickness | | | | |
|---|---|---|---|---|---|---|
| | | X | IV | VI | VII | V |
| **Min. thermal resistance** @ 75°F (24°C) | F·ft²·h/Btu | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 |
| | K·m²/W | 0.88 | 0.88 | 0.88 | 0.88 | 0.88 |
| **Max. water vapor permeance** | perm | 1.5 | 1.5 | 1.1 | 1.1 | 1.1 |
| | ng/Pa·s·m | 86 | 86 | 63 | 63 | 63 |
| **Max. water absorption by volume** | % | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 |
| **Min. Density** | lb/ft³ | 1.30 | 1.45 | 1.80 | 2.20 | 3.00 |
| | kg/m³ | 21 | 23 | 29 | 35 | 48 |

# Displacement of membrane asphalt under a planter with drainage channels cut into the insulation

# Insulation Various Types
# Moisture Absorption 21 Days




Curve A - 2.54 cm thick fiberboard, 169.8 kg/m$^3$
Curve B - 2.54 cm thick bead polystyrene, 26.2 kg/m$^3$, 31% void
Curve C - 5.33 cm thick bead polystyrene, 26.8 kg/m$^3$, 27% void
Curve D - 3.56 cm thick bead polystyrene, 21.3 kg/m$^3$, 27% void
Curve E - 5.08 cm thick bead polystyrene, 19.7 kg/m$^3$, 37% void
Curve F - 5.08 cm thick bead polystyrene, 16.5 kg/m$^3$, 27% void
Curve G - 5.08 cm cellular glass, 133.9 kg/m$^3$
Curve H - ■ 5.08 cm thick polyurethane, 50.1 kg/m$^3$, aluminum skins
○ 2.54 cm thick polyisocyanurate, 41.3 kg/m$^3$, aluminum skins, glass reinforced.
Curve I - ● 5.08 cm thick German bead polystyrene, 35.6 kg/m$^3$, 10% void
▲ 3.56 cm thick extruded polystyrene skinboard, 36.5 kg/m$^3$
□ 3.81 cm thick extruded polystyrene skinboard, 46.5 kg/m$^3$

FIG. 2—*This test measures the percent volume of water absorbed per unit volume of foam. The 96-h test is described in ASTM Method D 2842-69. Since longer periods of submersion can occur in the USD application, the test was run for 504 h (21 days).*

# Insulation Various Types
# Moisture Diffusion for 21 Days

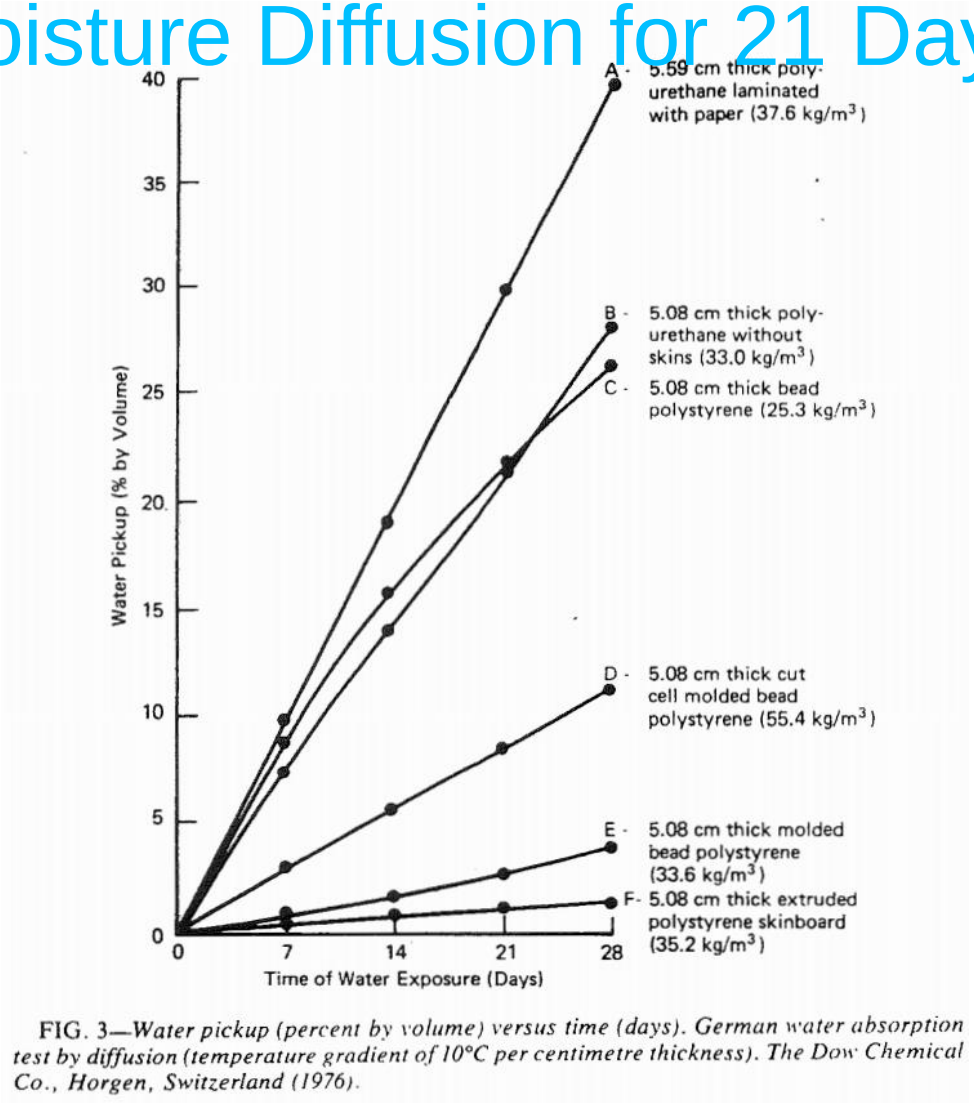
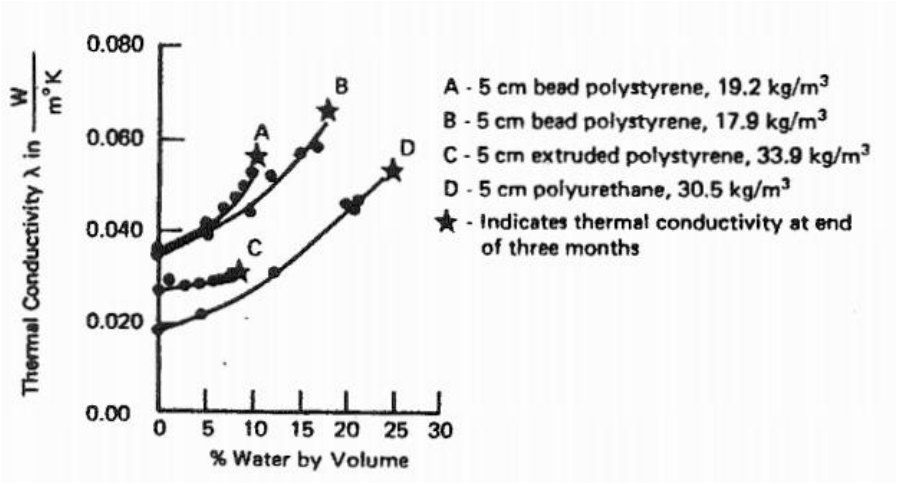
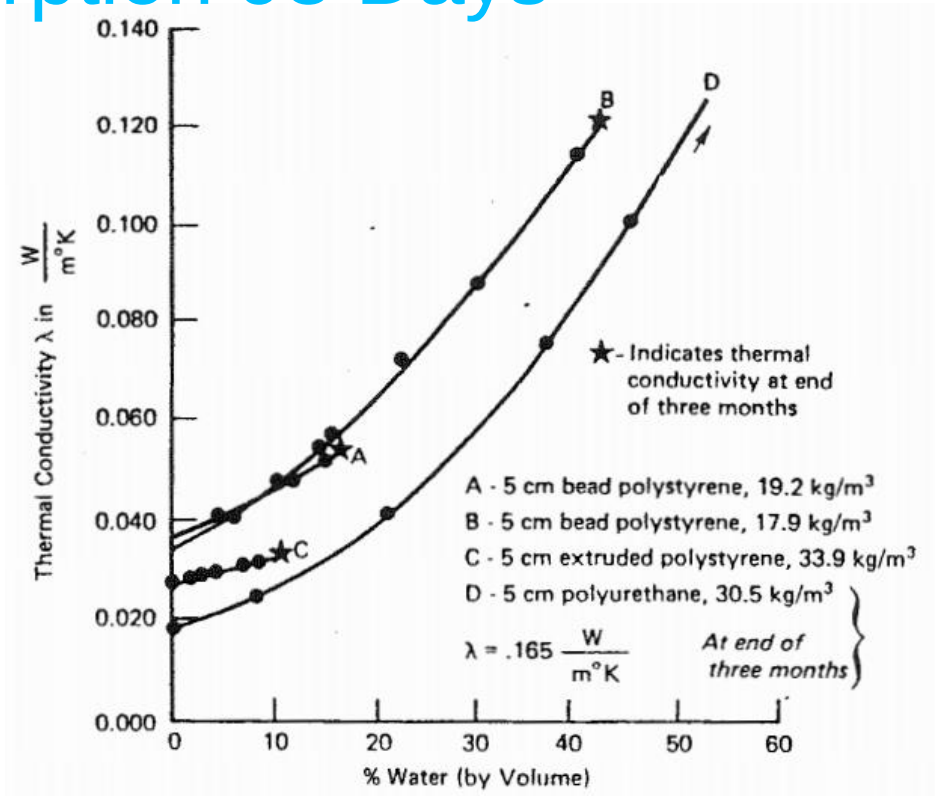



FIG. 3—*Water pickup (percent by volume) versus time (days). German water absorption test by diffusion (temperature gradient of 10°C per centimetre thickness). The Dow Chemical Co., Horgen, Switzerland (1976).*

# Insulation Various Types
# Moisture Absorption 93 Days

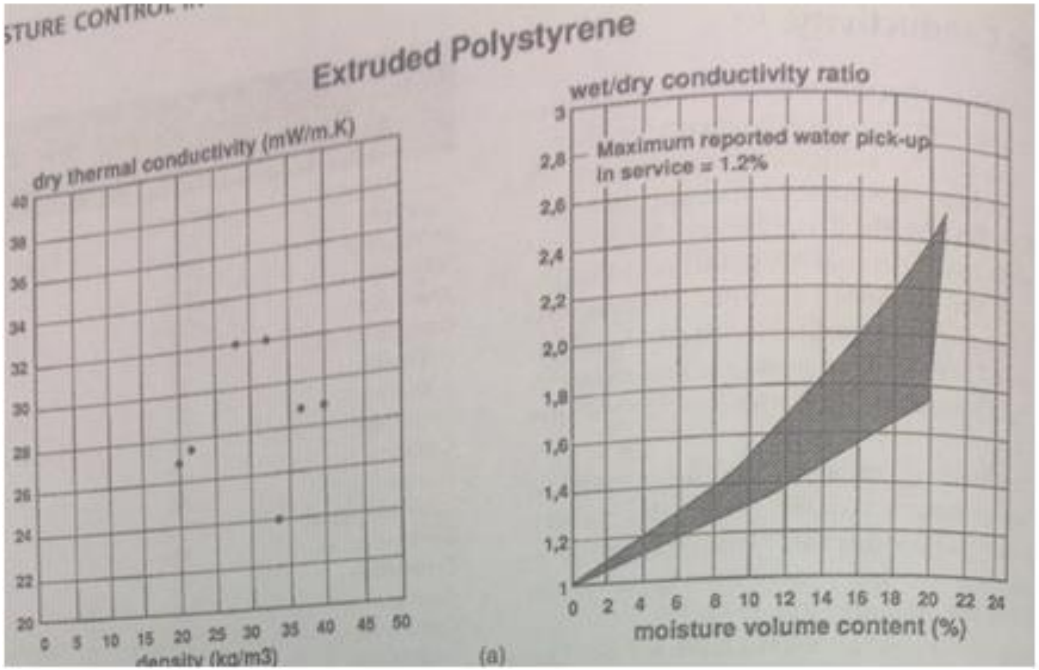



IG. 8—*Effect of moisture absorption on thermal efficiency of insulation sture barrier on the cold side of the insulation* [6].

# Average Suite Temperature

- XPS has the best thermal performance due to its resistance to water absorption compared with other insulation types
- Moisture accumulation in XPS causes its thermal resistance decrease.



# Test Samples

- All XPS sample are collected from inverted roof assemblies on sites:
  - from 11 – 30 years old
  - Installed in plaza roof, open rooftop parking, covered parkade or apartment deck
  - from the low slop roof and deck (1.5 – 2.0% slope)

- XPS boards are separately sealed in plastic and delivered to BSCE lab.
- The XPS insulations are all 1 ½” (38 mm) thick.
- The samples are covered by pavers with sand, brick pavers or concrete (cast in place).
- No roof assemblies have drainage mats above XPS insulation. No roof assemblies provide a” diffusion open layer” beneath XPS insulation, neither.
- All XPS situated directly on roof membrane and may effectively sealed to the membrane by Ballast.
- Samples collected in May to Aug may start to dry before sampling.

# Average Suite Temperature

| | Dry Density (kg/m3) |
|---|---|
| EPS | 30 |
| XPS | 26 |

| | Measured R-Value | Average |
|---|---|---|
| Dry EPS_1 | 4.5 | |
| Dry EPS_2 | 4.5 | 4.5 |
| Dry XPS_1 | 5.0 | |
| Dry XPS_2 | 5.0 | 5.0 |
| Soaked_EPS_1 | 3.7 | |
| Soaked_EPS_2 | 3.9 | 3.8 |
| Soaked_XPS_1 | 4.9 | |
| Soaked_XPS_2 | 4.8 | 4.8 |

| | |
|---|---|
| Dry EPS and XPS R-value Difference (%) | **10** |
| Soaked EPS and XPS R-value Difference (%) | **22** |

| **R-value reduction due to moisture-soaking (%)** | |
|---|---|
| EPS | **15.7** |
| XPS | **3.0** |