Osmosis and the Blistering Of Polyurethane Waterproofing Membranes

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ABSTRACT

Cold-applied asphalt-modified elastomeric polyurethane waterproofing membranes (polyurethane membranes) have been popular for roofing and waterproofing applications in the Pacific Northwest and British Columbia for at least the past 15 years. Their relative low cost and easy application resulted in their widespread use in inverted roof and waterproofing membrane assemblies (IRMA), applied to concrete decks. However, water filled blisters under these membranes have been discovered on numerous buildings in the Pacific Northwest in recent years. In some cases, the blisters were so large that replacement of the membrane was required. Water leakage to the interior can result when the blister expands to a crack or joint in the concrete slab.

The local building science and roofing industry is aware of the problem. However, there is a lack of understanding of the causal effects and the moisture transfer physics involved. Water vapour diffusion and capillary flow do not adequately explain the pressures or volumes of water contained within these discrete water blisters. Moisture transfer via osmosis can result in blisters under significant pressure and potentially explains the observed conditions. Osmosis is the physical transfer of water through a semi-permeable membrane when separating solutions of different dissolved ion (salt) concentrations. Under osmotic pressures, water will flow through a membrane from the less salty side to the more salty side in an effort to reach equilibrium.

A series of laboratory experiments were performed to demonstrate that the required conditions for osmosis to occur exist in the field. Laboratory testing of several of these membranes confirmed they are semi-permeable to water (in order of 1 to 8 US Perms for typical thicknesses). We also confirmed a significant dissolved salt-ion concentration in the water collected in the field from beneath the membranes.

Finally, osmotic flow was measured through several of the membranes using a controlled laboratory apparatus. The measured flow through these membranes in the laboratory is in the correct order of magnitude to explain the large water filled blisters and pressures observed in the field.

This paper demonstrates osmotic flow through polyurethane membranes and attempts to create an industry awareness of the issue. Ongoing research is underway to refine polyurethane waterproofing membranes to reduce their susceptibility to osmosis and prevent future occurrences of water filled membrane blistering.

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INTRODUCTION

Over the past several years, we have reviewed dozens of asphalt-modified polyurethane membrane applications ranging from 5 to 15 years of age. The membranes are applied to sloped concrete slabs in both insulated and un-insulated inverted roof and waterproofing membrane assemblies (IRMA's). Typically, water filled blisters have formed between the membrane and the concrete deck and are often under considerable pressure. These self-contained, pressurized water blisters have no identifiable leakage path through or around the membrane. Blisters range in size from a penny to entire roof deck areas and can contain significant quantities of water. In some cases, large blisters (>2" deep) have displaced concrete pavers, creating hazardous walking conditions. As blisters extend over cracks or joints in the concrete, water can leak to the interior.

In our experience in the Pacific Northwest, the blisters described above have been observed with asphalt-modified polyurethane membranes used in IRMA construction and not in other conventional roofing systems such as hot rubberized asphalt or sheet applied SBS modified bitumen. In an IRMA, the membrane is installed directly on the structural concrete, beneath insulation (if separating heated space) and a ballast or wear course. In the wet Pacific Northwest climate, moisture remains in contact with the membrane for much of the year.

Hygrothermal analysis shows that vapour diffusion can transport water through polyurethane membranes due to their relatively high vapour permeance compared to other roofing and waterproofing membranes (>1 US Perm vs <0.01 Perm). However, the quantity of water transported by vapour diffusion is not in the order of magnitude required to explain the blistering, nor are water vapour pressures sufficient to explain the high hydrostatic pressures that exist within the blisters.

To explain the large volumes of water and high pressures within the blisters, we hypothesize that osmosis is acting to transport water through the membrane. In the roofing industry, the concept of water flow by osmosis is uncommon. The process of osmotic flow has been reported to fail flooring and traffic membranes, and is a consideration in the design of bridge decks and water tanks which are exposed to groundwater, salt-water or road de-icing salts. It is also a reported problem in the design of glass fiber-reinforced boat hulls, where osmosis can form blisters within the fiberglass.

Objectives

The objective of this research study is as follows:

- Confirm that osmotic flow is a significant contributor to the observed in-situ blistering of polyurethane membranes directly applied to concrete in IRMA construction.
- Develop a test method to determine the susceptibility of a membrane to osmotic flow and measure the rate of osmotic flow under various salt concentrations.
- Determine a possible relationship between water vapor permeance and osmotic flow.
- Create awareness and highlight the need of osmosis control for the inclusion in current Canadian and US standards for liquid applied waterproofing membranes.

Background

Asphalt-modified polyurethane membranes have been used in hundreds of buildings constructed over the past 15 years in the Pacific Northwest and Lower Mainland of British Columbia. Their relative low cost and easy application have lead to its widespread use in IRMA construction, both insulated and un-insulated as well as for planters, fountains, and foundation walls.

Our firm and other local consultants have reviewed dozens of buildings where the polyurethane membranes have blistered. Blisters are also a frequent occurrence in fluid-applied polyurethane membranes in Japan (Tanaka et al 2007 & 2008). Water-filled blisters range from penny sized to those that encompass entire decks (Figures 1 & 2). Unlike vapour blisters filled with air, caused by other mechanisms, these blisters are filled with water under considerable pressure. Larger blisters can lift ballast and pavers, creating a hazardous “water-bed” effect when walking on the surface (Figures 3 & 4). Small blisters typically do not result in direct leaks to the interior; however, larger blisters that encompass a crack or joint in the concrete, tend to manifest into leaks to the interior.

Figure 1 & Figure 2: Typical Blistered Roof Membranes. Blister size ranging from penny sized blisters to areas several square feet, membrane 5-10 years old.

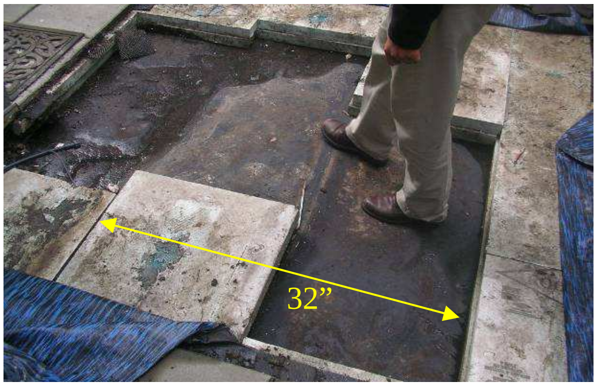


Figure 3: Large “water-bed” type blister lifting pavers over entire deck

Figure 4: Water beneath blistered membrane

Investigating IRMA construction is challenging because ballast and insulation need to be removed to expose the membrane. As a result, only small, random areas of the membrane are typically reviewed. Larger areas of membrane typically only get exposed when leaks are reported, when blisters have become so large that they lift up the ballast or pavers, or when the membrane is replaced.

Blisters typically occur on horizontal surfaces, but also have been observed on vertical surfaces of water features, planters and green roofs. In IRMA construction located in the Pacific Northwest, it is not uncommon for water to remain at the membrane surface year-round. When inverted roofing and waterproofing are investigated in the summer, even after many weeks of dry weather, water exists at the membrane surface, held by capillary forces between the membrane and insulation/drainage matt layer and prevented from evaporating by the dimpled polyethylene drain mat or insulation installed above.

In our experience the following factors appear to increase the severity and size of the blisters:

(a) Blisters are often more severe at low points and at areas of poor slope, i.e., ponding. However, blisters still do occur where the slab is well sloped to drains.
(b) Blisters are typically larger and more prevalent at areas where the membrane is thinner.
(c) The size or severity of the blisters does not appear to be affected by the use of either drainage mat or extruded polystyrene insulation applied directly over the membrane.
(d) Blisters are almost always larger and more frequent in older membranes.

In our review of available literature, we found little information regarding the blistering of polyurethane membranes in IRMA construction suggesting the mechanisms causing the failure are not well understood by the roofing and waterproofing industry.

MECHANISM OF MEMBRANE BLISTERING

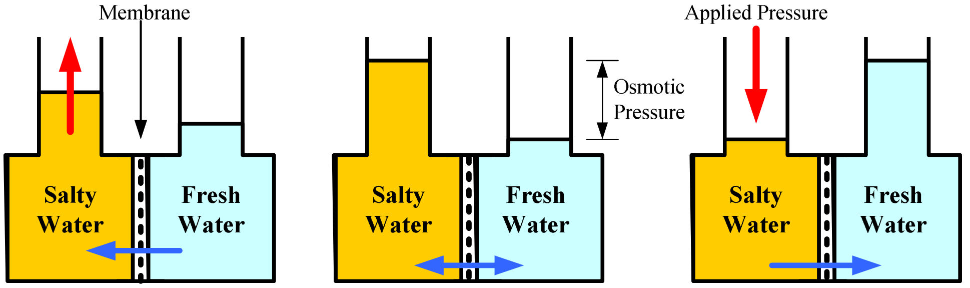
Osmosis Process

Osmosis is a naturally occurring phenomenon, where water (or other solvent) flows through a semi-permeable membrane from a solution of low salt (solute) concentration (hypotonic) to a solution of high salt concentration (hypertonic), without the input of energy (Oxtoby et al 1999).

Osmosis can be countered by increasing the pressure of the hypertonic solution with respect to the hypotonic side. Osmotic pressure is the pressure required to maintain equilibrium between the two sides, with no net movement of solvent. Osmotic pressure depends only on the molar concentration of the solute, not the type of solute present. Therefore, if any difference in solute is present across a membrane, osmosis will occur.

Essentially, if a semi-permeable membrane separates a tank of fresh and salt water, the fresh water will flow through the membrane to the salty side until equilibrium (equal concentration) is achieved. If left unrestrained, fresh water would essentially fill up the salty side until the water head pressure is equal to the osmotic pressure. The semi-permeable membrane must be permeable to the solvent (i.e. water), but not to the majority of solutes (salt, metal, and contaminant ions), otherwise equilibrium will be achieved by dissolution through the membrane. Depending on the molecular structure and pore size of the membrane, certain salt ions may pass through freely, while other larger and heavier metal ions may not. In this case, osmosis will still occur.

Reverse osmosis utilized in water filtration systems, essentially applies a high water pressure (>50 psi) to counter-act the osmotic pressure and force water ions through a specially developed semi-permeable membrane to create fresh water. Reverse osmosis membranes have been developed with these properties in mind, to only allow H_2O ions to pass through, rejecting other larger salt ions with greater than 99% effectiveness. The processes of osmosis and reverse osmosis are demonstrated in Figure 5.



Osmosis: Water Flows from Low Concentration of Salt to Higher Concentration

Equilibrium: Osmotic Pressure is the pressure required to stop water flow and reach equilibrium

Reverse Osmosis: Pressure greater than osmotic pressure is applied to filter salt-ions out and create fresh water

Figure 5: Osmosis, Equilibrium and Reverse Osmosis Flow through a Membrane

The two laws governing the osmotic pressure of a dilute solution were discovered by the German botanist W. F. P. Pfeffer and the Dutch chemist J. H. van ’t Hoff (Oxtoby et al 1999). The laws state that the osmotic pressure of a dilute solution at a constant temperature is directly proportional to its concentration, and that the osmotic pressure of a solution is directly proportional to its absolute temperature. Osmotic pressure is analogous to Boyle's law and Charles's Law for gases. The ideal gas law, PV = nRT, has an analog for ideal solutions in the form of $\pi V = nRTi$. This is rearranged in Equation 1 in terms of molar concentration and solving for osmotic pressure, π.

$$\pi = i \cdot M \cdot R \cdot T \qquad (1)$$

Where, π = osmotic pressure; i = the number of ions produced during dissociation of the solute, M = the molar concentration of all solutes, moles/L; R = 8.3145 J/K·mol (0.083145 L·bar/moles·K) the molar gas constant; and T is absolute temperature, Kelvin.

In solutions containing multiple types of dissolved salts, the partial osmotic pressure for each is summed to determine the overall osmotic pressure across the membrane. Essentially it is the difference in total dissolved solids (TDS) that causes the pressure. Reverse osmosis membrane manufacturers have simplified this formula to the following in terms of pressure in psi to size reverse osmosis filtration systems. (Lenntech 2008):

$$\pi = 1.12 \cdot T \cdot \sum m_j \qquad (2)$$

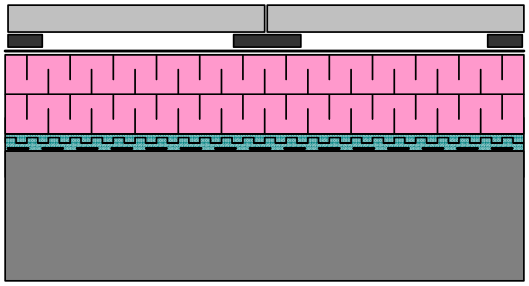
Where, Σm_j is the sum of molality concentration of all constituents in a solution (moles of solute/kg of solvent) and T is the absolute temperature in Kelvin.

For example, salt water from the ocean will have a total dissolved solids concentration of approximately 36,000 mg/L or ppm (Lenntech 2008). This concentration has a total osmotic pressure difference of almost 26 bar (2.6 MPa) at 20°C. Brackish water, (i.e. well-water contaminated with ground salts) may have a total dissolved solids concentration of 500 mg/L which results in a pressure of 0.25 bar (25 kPa) at 20°C. These osmotic pressures give an indication of the pressure required in a reverse osmosis filtration system.

Blistering Process

We hypothesize that the formation of a blister occurs in two stages. In stage 1, a film of liquid water forms at the concrete to membrane interface, likely at a surface void in the concrete beneath the membrane. Various sources can form the initial film of water including vapor diffusion and capillary flow downward through the polyurethane waterproofing membrane or water initially in the concrete slab from construction or rainwater. Once a film of water forms, vapour pressures on both sides of the membrane are equal and vapour diffusion ceases. In stage 2, the water film dissolves minerals from the concrete increasing the salinity. Once this osmotic cell starts, osmotic pressures draw water through the membrane, creating water-filled blisters. As the pressure in the blister increases it de-bonds from the concrete at the perimeter enlarging the blister and allowing the process to continue and the blister to grow in size over time.

A typical IRMA is depicted in Figure 6. Rainwater flows down through the ballast, insulation and drainage layers to the waterproofing membrane. Throughout the wetting process, water is adsorbed on the surfaces and into the pores of the materials within the assembly, remaining there even after the bulk of the rainwater is drained away. This creates a layer of water and vapour at 100% RH at the membrane surface.



- Concrete Pavers or Ballast
- Pedestals (Optional)
- Filter Fabric
- Extruded Polystyrene Insulation (2-4")
- Molded Polyethylene Drainage Matt (Optional)
- Cold-Applied Polyurethane Roof Membrane
- Concrete Slab (6-8")

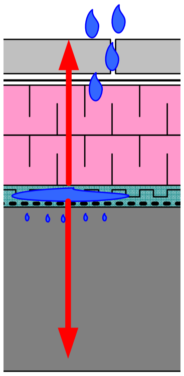
Figure 6: Typical IRMA Waterproofed with a Polyurethane Membrane

Extruded polystyrene has a vapour permeance of approximately 15 ng/Pa·s·m^2 (per 100 mm), and drainage mat, made of dimpled high-density polyethylene has a vapour permeance of less than 1 ng/Pa·s·m2. The ability of an IRMA to dry upwards by vapour diffusion through these materials is limited. The concrete also has a relatively low vapour permeance, with a wet permeability estimated from 0.5 to 5 ng/s·m·Pa (WUFI 2009, ASHRAE 2005, Onmura et al. 2009). Thus a 150mm thick slab has a vapour permeance ranging from 3 to 30 ng/Pa·s·m^2. Interior ceiling finishes or coatings will reduce this further. The vapour pressure differences during wet periods of the year are shown graphically in Figure 7.

Typical Wet
Month Exterior
Conditions 10°C /
>90% RH
VP = ~1200 Pa

Membrane Interface
Conditions
20°C / 100% RH
VP = 2200 Pa

Typical Indoor
Conditions
21°C / 50% RH
VP = ~1200 Pa



Vapour Pressure
Drive to exterior ~
1000 Pa

Vapour Pressure
Drive to interior ~
1000 Pa

Figure 7: Vapour Drive from Saturated Roof Membrane Interface to the Interior and Exterior

Even during the warmer summer months, and under solar heating, the insulation above the membrane maintains the concrete temperature relatively constant, and as a result, minimal heat is provided to dry out the excess or absorbed water. Field experience and hygrothermal modeling show that even when bulk surface water dries out, the relative humidity above the membrane remains above 90% year round, maintaining a constant vapour pressure drive from the exterior to the interior. Therefore, whether liquid water or water vapour is present at the roof membrane surface, there will be an almost constant vapour pressure drive inwards, which will effectively prevent significant drying from occurring upwards through the membrane. As a result, indoor humidity and temperature do not have a significant effect on the amount or severity of blistering. This is supported by our field observations of blistered membranes over all types of occupied and unoccupied spaces including occupied residential suites, mechanical rooms, pools, parking garages, and exterior spaces.

Figure 8 depicts the concrete moisture content output from a seven year WUFI 4.1 hygrothermal simulation of the inverted roof assembly discussed above with two different membrane vapour permeance. The plot compares a 30 mil polyurethane membrane (vapour permeance = 400 ng/Pa·s·m^2) and a two-ply SBS membrane (vapour permeance < 1 ng/Pa·s·m^2). WUFI does not account for moisture flow by osmosis, but does model vapour and capillary transport through the membrane and concrete. The impact of rainwater wetting and sitting on the membrane between rain events was accounted for in the model; however, note that the waterproofing membrane was assumed to have no capillary suction, consistent with other membrane material properties listed in the WUFI database.

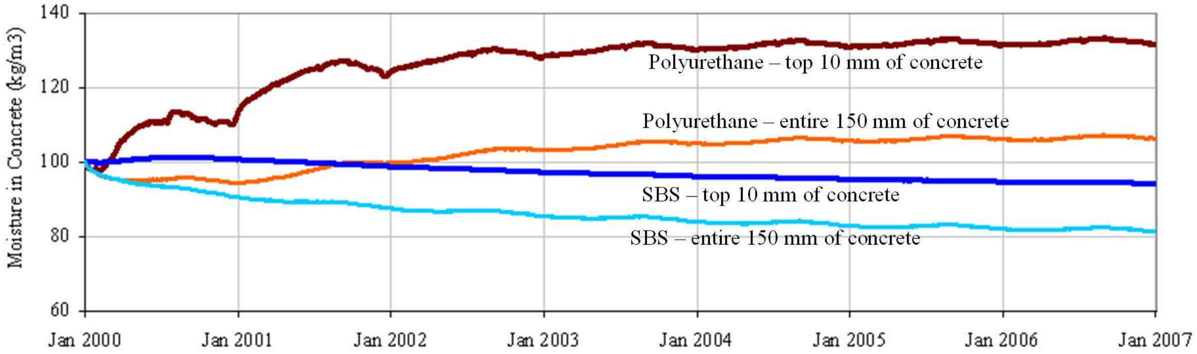
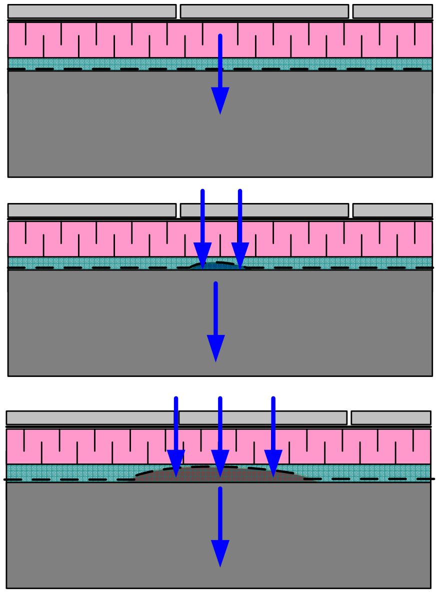


Figure 8: Modeled Moisture Content of Concrete Slab with SBS and Polyurethane Waterproofing

The simulation demonstrates that the polyurethane membrane will allow a net wetting of the concrete from vapour diffusion. During a typical year, more moisture is transported through the membrane into the concrete, than can dry out of the concrete itself. This analysis is sufficient to show that over time the concrete under the membrane will become saturated. However, once the top surface of the concrete becomes saturated, the vapour pressure will be equal on both sides of the membrane, diffusion will stop and there will be no driving pressure to create a blister.

Once the concrete is wet, salt ions in the concrete aggregate, cement and admixtures dissolve into available water at the surface. This dissolution of ions from the concrete creates the required salt concentration difference between the top and bottom of the membrane for osmosis to begin. Once started, osmosis continues until the salt concentration gradient is removed, or water is removed from the fresh water side of the membrane. The process is slow to start, but accelerates rapidly once small quantities of liquid water are present beneath the membrane. The osmosis mechanism is summarized in Figure 9.



Water sits on top of membrane, held by capillary beneath insulation or due to poor drainage of the concrete surface

Vapour diffusion moves moisture through the membrane. Concrete is less permeable than membrane and water begins to saturate the concrete and accumulate at the membrane interface.

In the accumulated moisture, mineral ions leach out of the concrete slab increasing the salt concentration of the water beneath the membrane. Osmosis begins and small blisters are formed.

Vapour diffusion to interior through concrete is relatively slow compared to the rate transported by Osmosis.

Osmosis transfers new rainwater through membrane into blister which is at a much higher salt concentration. As the blisters expand, more salts dissolve out of the concrete increasing the salt concentration gradient. Blisters continue to grow until membrane ruptures or leaks occur through concrete at a crack or joint.

Figure 9: Blister Formation Mechanism by Osmosis

HYPOTHESIS OF OSMOTIC FLOW

For osmotic flow to occur across a membrane, two requirements must be satisfied:

1. The membrane must be semi-permeable to water molecules and not salt molecules, and
2. Liquid water of different salt concentrations must be present on both sides of the membrane.

To prove the hypothesis that osmotic flow can occur across polyurethane membranes, samples of membrane and water from the blisters were collected from several buildings. The water vapour permeability of the blistered membranes was measured and the sampled water analyzed to determine the salt ion concentration of both the blister water and the water collected from the top surface of the membrane.

Water Vapour Permeance Testing of Polyurethane Roof Membranes

Water vapor permeance of the sampled polyurethane membranes was measured under dry-cup, wet-cup, and inverted wet-cup conditions in general conformance with ASTM E96. Vapour permeance of new polyurethane membrane samples provided by several manufacturers and control samples of other waterproofing membranes were also measured for comparison. Vapour permeance test results correlated with published and unpublished data provided by the membrane manufacturers.

Measured water vapour dry-, wet- and inverted wet-cup permeance data for three different polyurethane membranes are provided in Figure 10. Results for 3 low-permeance roofing membranes are also shown for comparison purposes. Inverted wet-cup testing (wet-cup sample inverted so that liquid water is in direct contact with sample) is not always performed by most roofing membrane manufacturers, but provides the best indication of vapour permeance under realistic exposure conditions for a membrane in an IRMA system.

Two of the results are for aged polyurethane membrane samples removed from site - Membrane #1 and #2, both approximately 10 years old. Membrane #3 is a new sample of a similar polyurethane membrane, from the same manufacturer as Membrane #1. The installed membrane thickness of 30 and 60 mils for Membranes #1 and #2 are considered thin by today's standards, but were common in the Vancouver market 5 to 15 years ago.

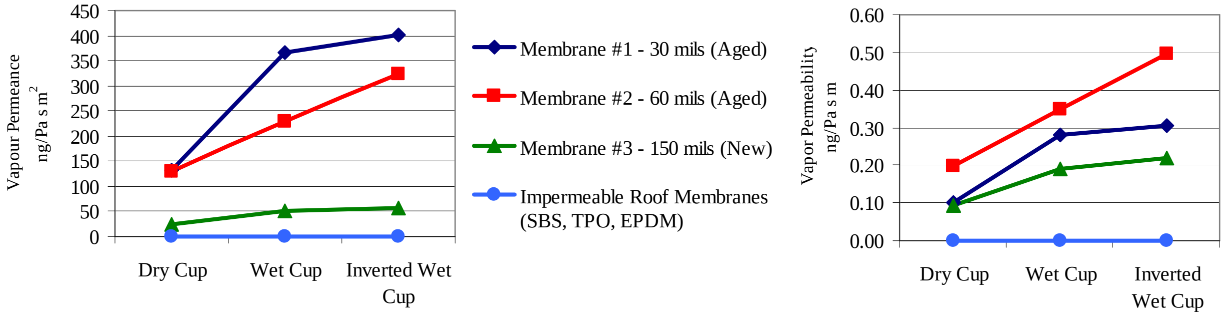


Figure 10: ASTM E96 - Vapour Permeability and Permeance Laboratory Results for Membrane Samples, 1 US Perm = 57.4 ng/Pa s m^2

The results show that the polyurethane membranes are relatively permeable compared to other roofing and waterproofing membranes, especially inverted wet cup measurements. The relationship between water vapour permeance and osmotic flow through a membrane is not fully understood at the micro-porous level; however, we believe they are intrinsically related. If the membrane has a measureable water vapour transmission rate, then it makes sense that it will have an "osmotic flow" transmission rate as well. If the membrane pore structure allows the passage of water ions, but not all dissolved salt and metal ions, then osmotic pressures can be developed.

Water Absorption of Polyurethane Membranes

Water uptake testing of the polyurethane membrane samples was performed to determine if water absorption is related to osmotic flow. If a material will absorb water into its pore structure, it follows that water may also be able to flow through it.

Membrane samples were submerged in water for over three months and weighed periodically until the mass remained constant for longer than 2 weeks. Both aged membrane samples absorbed approximately 16% to 17% moisture content by mass and the new membrane sample absorbed approximately 4%. Moisture absorption in all samples generally stopped after 2 to 3 weeks. The higher absorption in the aged samples may be due the polyurethane filler materials and reinforcing mesh fabric used by both manufacturers at the time. These water absorption tests appear to indicate that water is able to pass through the pore structure of these membranes.

Dissolved Salt Concentration of Blister Water

Samples of water and membrane at large blisters from two different buildings were collected for laboratory testing. The water was analyzed to confirm different salt concentrations between samples collected from above and below the membrane. Samples of water were extracted from the membrane blister with a syringe and small hand-pump, and collected from above the membrane (rainwater). Both samples were sent to an independent laboratory for analysis of dissolved metals concentration. At a large blister in Membrane #1, approximately 12 inches of hydrostatic water head (~3 kPa) was measured prior to the extraction of the sample water. The water inside the blister had a dark brownish tint, similar to all of the blisters reviewed, and is likely to be the result of continual contact with the bitumen in the asphalt-modified polyurethane membrane.

Figure 11 & Figure 12: Cutting of Membrane Blister and expulsion of water during extraction process.

A water quality laboratory analysis determined the dissolved solid concentration for 30 of the most common dissolved metal ions. Table 1 includes the results provided by an independent water testing laboratory of the membrane blister water and rainwater taken from one of the buildings where Membrane #1 was used.

Table 1: Dissolved Metals Concentration – Building 1 (30 mil membrane sample)

	Water from Beneath Membrane #1 (Blister Water)	**Water from Above Membrane, (Rainwater)**
Soluble Metal Ions in Solution	*Dissolved Solid Concentration, mg/L, ppm*	*Dissolved Solid Concentration, mg/L, ppm*
Sodium	2960	1.89
Potassium	574	0.47
Sulphate	75.3	<1.0 ppm
Magnesium	1.83	0.35
Phosphorous	1.82	<0.2 ppm
Silicon	29.9	<1.0 ppm
Calcium	3.4	4.0
Other Dissolved Metals	Trace amounts of several, <1ppm	None present
Total Dissolved Solids	~3650 ppm	~7 ppm
Hardness, CaCO3 equivalent	16.0	11.5

As suspected, the blister water had high levels of several dissolved metal ions, the majority of which were sodium and potassium ions. The mix of dissolved metal ions at the blister water is likely from minerals within the aggregates, cement, admixtures, and polyurethane membrane itself. The presence of silicon, present in cement (calcium silicates $CaO{\cdot}SiO_2$), indicates dissolution from the concrete. The level of dissolved ions within the blister water was considerably higher than rainwater and for reference is more saline than brackish water, but much less than seawater.

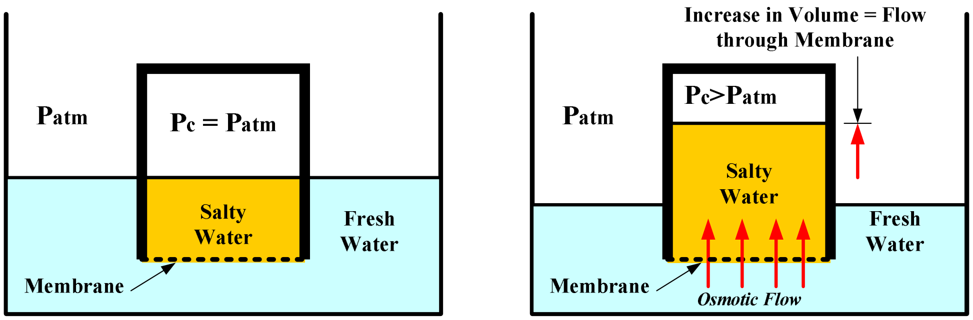
Initial calculations predict that an osmotic pressure of approximately 326 kPa was present at this blister. While this pressure could not have been physically contained within this elastic membrane, it is better visualized as a *pressure potential* which causes *suction* of liquid water through the membrane. In reality the pressure within the blister is moderated by failure of the membrane-to-concrete bond at the sides of the blister and stretching of the membrane under tensile stresses.

VERIFICATION OF OSMOTIC FLOW

Apparatus

To measure osmotic flow through the membranes, the following apparatus was developed and tested. A piece of the polyurethane roof membrane is used to separate distilled and salt water. If osmosis flow occurs across the membrane, water will flow from the distilled water reservoir through the membrane and into the salt water until equilibrium occurs or the pressure developed in the container is equal to the osmotic pressure (Oxtoby et al 1999). By measuring the mass and volumetric change of the container containing the salt water and membrane at regular intervals, the osmotic flow can be measured.

Distilled water was used to represent rainwater, and water removed from several membrane blisters was used as the salt water. Polyurethane and other roofing membranes, ranging in thickness from 30 to 150 mils were tested, as was a commercial reverse osmosis membrane as a proof of concept exercise. Figure 13 demonstrates a concept of the apparatus and Figure 14 shows a schematic of the container and photograph of one of the proof of concept test specimens.



Initial Setup, Pressure within Container is equal to atmospheric.

Osmosis occurs until Pressure within container reaches the Osmotic Pressure

Figure 13: Osmotic Flow Testing Apparatus Schematic

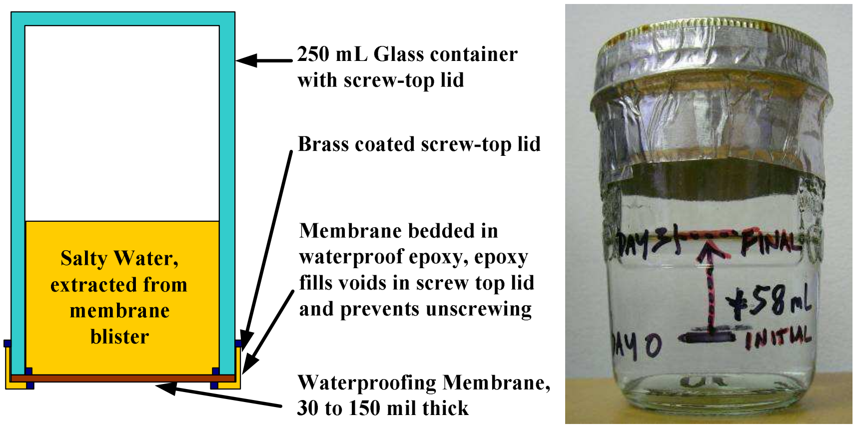


Figure 14: Osmotic Flow Testing Container Schematic and Photograph of Increase in Water Volume

As a proof of concept experiment, a commercial reverse osmosis water filter was disassembled and a sample of the osmotic membrane put into the apparatus with the blister water removed from site. Other salt-solutions using common table salt were also tested. Flow through the membrane initially was in the order of 15 L/m^2/day before immense pressures developed in the containers. This order of flow is comparable to what is advertised by the osmosis membrane in a water filtering application. As a result of the high pressures developed, several of the container lids burst during the test procedure. In Figure 14, a total of 58 mL (25 L/m^2) of water was transported through the reverse osmosis membrane, as was measured in the container at the end of 31 days.

Procedure

Samples of polyurethane membranes discussed in the previous sections were tested using the osmotic flow test apparatus. Samples of salt water removed from the blisters were used in conjunction with the membrane samples to demonstrate osmotic flow under the specific field conditions. Initial testing focused on two of the aged polyurethane membranes (#1 and #2). Samples of the membranes and salt water from the blisters were put into the test apparatus and tested as follows:

1. Samples of membrane are cut to precisely fit into the screw top ‘open top’ lid of the glass jar. Each sample is initially weighed and the thickness is measured.
2. A known mass of salt water is placed into the glass jars.
3. Membrane samples are bedded into waterproof epoxy within the lid flange of the glass jar. Epoxy is also used between the membrane and the glass. The screw-top lid provides compression and a watertight fit of the membrane at the edges. The membrane acts as a gasket; however, waterproof epoxy is used to aid with sealing the membrane in place and to seal the container shut.
4. After the epoxy has cured and the container is leak tested, the initial mass of the container, membrane, and salt water together is measured.
5. Membrane coupons (blank samples) are produced, measured, weighed and submerged in the fresh water bath. The water level of the fresh water is kept equal to that within the container to eliminate the effect of hydrostatic pressure head.

6. At regular intervals, the containers and blank samples are removed from the fresh water bath, dried thoroughly, and weighed. This process is repeated approximately twice a week for several months. For samples with significant osmotic flow (i.e. through an osmosis membrane), the volumetric increase can also be measured using graduations on the sample container.
7. The flow of water through the membrane is measured by subtracting the incremental mass from the initial container, water, and sample mass. The glass container, lid, and epoxy do not absorb water, (confirmed by producing empty container blanks and submerging them in water), so any change in mass is the result of absorption into the membrane and flow into the salty water within the container.
8. To isolate osmotic flow, the absorption rates of the membrane samples had to be known. For the two membranes tested, each gained approximately 17% moisture by mass within 3 weeks, and remained constant for the remainder of the test. Blank samples were used to determine the required time and mass of water for absorption to saturation to occur. Following this initial uptake, additional mass/volume gain of the containers is by osmosis flow through the membrane. This can also be confirmed by measuring the volume of water within the container and subsequent pressure developed.

Results

Measured osmotic flow rates through 30 and 60 mil samples of Membrane #1 and #2 are presented in Figure 15. Several additional samples of these membranes are currently being tested and show similar flow rates.

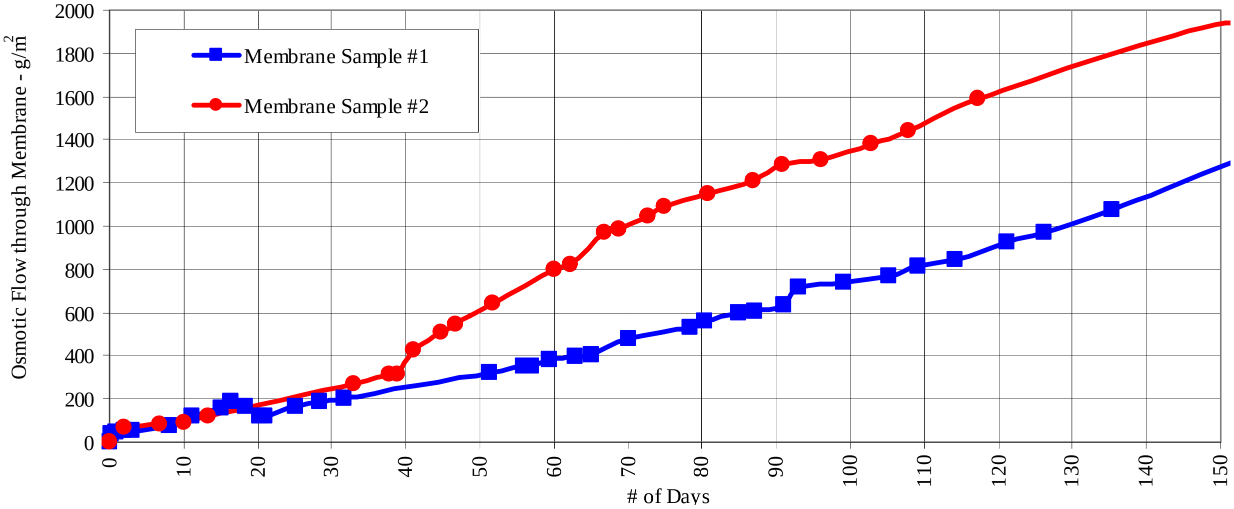
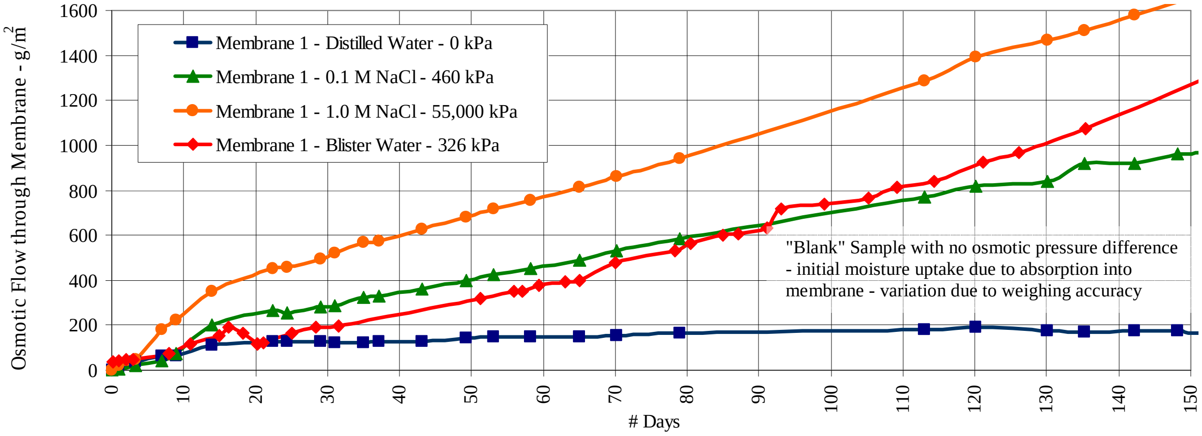


Figure 15: Polyurethane Membrane #1 and #2 – Measured Osmotic Flow through Membrane

Small deviations result from precision of weighing the samples (to nearest ±0.01g of container mass), but otherwise a constant flow rate was measured. With this setup, it appears to take a few weeks for the membrane to become fully saturated before osmotic flow rates can be determined. On average, an osmotic flow rate of between 8 and 13 g/m^2/day was measured.

As shown, both membrane samples have similar order of magnitude osmotic flow rates. Over time, the osmotic pressure should decrease with a decreasing salt-concentration; however, the volume of water needed to reach equilibrium is many times the size of the jars, thus we wouldn't expect to see a significant change in slope of the 150 day test period. However, as pressure develops within the blisters in the field and the membrane pore structure stretches and opens up, the osmotic flow rate may be affected. The blister water contains many different salt ions at varying concentrations, over time some of the low concentration salts will reach their equilibrium pressure reducing and marginally reduce the flow rate.

Further experiments are ongoing to determine the effect of the osmotic pressure and osmotic flow. Figure 16 shows initial results for 0.1 and 1.0 Molar NaCl salt solutions are compared to distilled water (blank sample) and the blister water.



"Blank" Sample with no osmotic pressure difference - initial moisture uptake due to absorption into membrane - variation due to weighing accuracy

Figure 16: Comparison of Osmotic Flow through Membrane #1 with different Osmotic Suction Pressures

Comparing the osmotic flow rates of the three salt solutions to the distilled water confirms that the salt concentration has a direct effect on the rate of osmosis through the polyurethane membrane. The lack of flow through the control distilled water sample also confirms that it is the process of osmosis which is pulling water through the membrane, and not capillary suction or another mechanism.

Based on continued research underway with new un-aged polyurethane membranes with and without various primer coatings, preliminary osmotic flow rates of 0.5 g/m^2/day to 7 g/m^2/day have been measured in the laboratory. The intent of this further research is to reduce the osmotic flow rate through new membranes to as close to zero as possible to prevent blisters from forming.

Discussion

The measured osmotic flow rate through the aged polyurethane membranes (with the salt water removed from the blisters) is, on average, between 8 and 13 g/m^2/day. For a membrane in an IRMA application continually exposed to water, in one year this flow rate equates to between 3 and 5 L/m^2 of water (3 to 5 mm deep) transported by osmosis. In ten years, this is in the order of 30 to 50 L/m^2 or water (30 to 50 mm deep), which corresponds to the volume contained beneath the membrane in blisters we have observed at several buildings. Blisters are often observed to be 3 mm to 25 mm tall and in extreme cases where the pavers are floated, greater than 50 mm.

Continuous exposure to liquid water will affect blister formation, and it is likely that some blisters may grow and shrink seasonally when liquid water is present on top of the membrane. In addition, both membrane adhesion and tensile strength of the membrane will affect how large the blisters grow in the field. Blisters will also stop growing if the pressure becomes equal to the osmotic suction pressure or if the blister does not continue to grow by adhesion failure or stretching which may occur at low salt concentrations and osmotic pressures.

In the IRMA application, the wetting of the concrete surface by osmosis is shown to be up to an order of magnitude higher than the drying capability of the assembly. Above the membrane the RH remains high, between 90% and 100% year round. As a result, drying outwards is slow through the insulation and drainage mat at rates of less than 0.1 g/m^2/day. On the bottom side, drying through the concrete is also a very slow process, and vapour flow inward through the concrete is estimated to be in the order of 1 g/m^2/day (dependant on concrete properties). These mechanisms for drying are slower than the wetting process, and moisture accumulates beneath the membrane. The osmotic cell develops immense suction pressures which cause blisters to form and expand, acting to delaminate and stretch the membrane. As the process progresses, the blisters expand into each other until very large water filled blisters develop.

CONCLUSIONS

Severe water filled blistering of cold-applied asphalt-modified elastomeric polyurethane waterproofing membranes is a frequent problem for inverted roof membrane assemblies in the Pacific Northwest. Our testing and research demonstrates that the formation of water-filled blisters can be explained by fluid transfer through osmosis. The research confirms that osmotic flow does occur through these membranes, the conditions for osmosis to occur exist in the field, and our test results replicate the same order of magnitude of moisture transfer observed in the field.

The rate of osmotic flow is a function of the vapour permeance of the membrane. Therefore, lowering the vapour permeability of the polyurethane membrane will likely reduce the potential for osmosis to start by reducing the potential for the top surface of the concrete to become saturated, and will likely result in a lower rate of flow under osmotic pressures.

The aged polyurethane membranes which were removed from blistered roofs and tested were found to be semi-permeable, and have a vapour permeance ranging from 60 to 420 ng/Pa·s·m^2 depending on application thickness and chemical composition. Some new polyurethane membranes which have also been tested have similar order of magnitude vapour permeance values (up to 120 ng/Pa·s·m^2) even when tested with certain concrete primers.

Osmotic flow rates measured through aged polyurethane membranes which were removed from blistered locations are in the order of 8 to 13 g/m^2/day. Preliminary testing has also been performed on new primed and un-primed polyurethane membranes which are currently available on the market, with measured flow rates of between 0.5 g/m^2/day to 7 g/m^2/day depending on membrane chemistry, thickness, and primer application. These lower flow rates are still in excess of most other waterproofing and roofing membrane systems, and at this time, it is not known if this flow rate is low enough to prevent blisters from occurring within the expected service life of the membrane. Further research is needed to develop an acceptable solution.

The two most relevant standards that cover the manufacture and installation of asphalt modified polyurethane membranes are ASTM C836-00 Standard Specification for High Solids Content, Cold Liquid Applied Elastomeric Waterproofing Membrane for Use with Separate Wearing Course, and CAN/CGSB – 37.58-M86 Membrane, Elastomeric, Cold-Applied Liquid for Non-Exposed use in Roofing and Waterproofing. These standards do not contain maximum values for vapour permeance, requirements for reporting inverted wet cup permeance numbers, or osmosis testing requirements. Based on the field observations and the testing performed in this study, the existing standards do not have adequate test requirements to prevent premature blistering of polyurethane membranes.

RECOMMENDATIONS

Awareness and understanding of the physical process of osmosis, and potential impact on building materials will help the industry come up with solutions and avoid the problem in the future.

We recommend including maximum allowable values for membrane vapour permeance, tested under inverted wet cup conditions, and osmosis testing requirements be included in current industry standards referenced by polyurethane membrane manufacturers, specifically ASTM C836-00 and CAN/CGSB–37.58-M86.

We also recommend that an industry-accepted test and standard be developed to test new IRMA roofing and waterproofing membranes for susceptibility to osmotic flow. Additional research is needed to determine allowable osmotic and vapour flow rates which can be safely accommodated by moisture flow through concrete slabs. The effect of aging and exposure to wet and alkaline conditions on the material properties of polyurethane membranes in the field should also further researched in this context. Research should also be performed to examine the effect of concrete primers and sealers to prevent the passage of salts to the membrane interface.

Based on these findings, new polyurethane membranes should be modified to be sufficiently impermeable to vapour and osmotic flow to prevent blistering within their expected service life, while still maintaining their other desirable physical properties for waterproofing.

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