Moisture Transport by Osmotic Flow through Waterproofing Membranes—Toward the Development of Osmosis-Resistant Membranes

Graham Finch
Associate Member ASHRAE

Brian Hubbs, PEng

Robert Bombino, PE
Associate Member ASHRAE

ABSTRACT

The transport of moisture by vapor, capillary, hydrostatic, or convective means through building materials is relatively well understood by the building industry. Building materials, particularly those in roofing and waterproofing applications are typically designed and marketed with these mechanisms in mind, with applicable test standards regulating their minimum performance. However, a recent series of cold-applied liquid polyurethane waterproofing systemic material failures caused by osmosis in the Pacific Northwest has shown the importance of this liquid moisture transport mechanism and a need for an industry test standard and material property requirements.

Osmosis is the physical transfer of water through a semipermeable membrane that separates solutions of different dissolved ion (salt) concentrations. Under osmotic pressures, water flows through a membrane from the less salty side to the more salty side in an effort to reach equilibrium (low to high concentration). As has been shown, waterproofing membranes separating rainwater from concrete (containing many readily dissolvable mineral ions) in inverted or protected roofing applications (i.e., where water sits on the membrane for prolonged periods in wet climates) are susceptible to osmotic flow. Over time, the flow of water through the membrane by osmosis can lead to water-filled blisters, membrane delamination, leaks, and the ultimate failure of the waterproofing membranes.

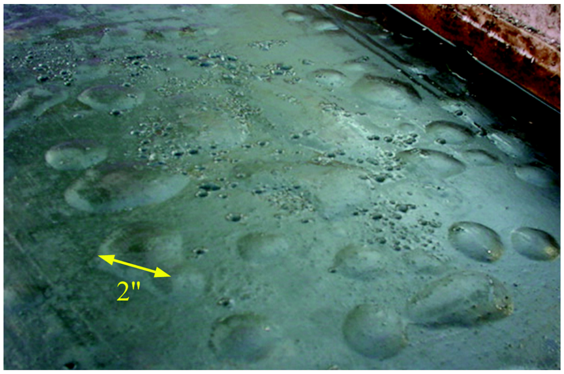
The paper presents a proposed test standard for osmotic flow through waterproofing membranes based on our research into the phenomena and laboratory testing over the past two years. Osmotic flow rates for several different old blistered and new membranes are presented in conjunction with inverted wet-cup vapor permeance values in an attempt set potential targets.

INTRODUCTION

Our firm has been reviewing in-situ performance and researching the systemic failures of asphalt-modified polyurethane membranes in the Pacific Northwest over the past several years. As a result of this research, we have identified widely used two products that tend to exhibit systemic water filled blistering after 5–10 years in service. The membranes are applied to sloped concrete slabs in both insulated and uninsulated inverted roof and waterproofing membrane assemblies (IRMAs). Asphalt-modified polyurethane membranes have been used on hundreds of buildings constructed over the past 15 years in the Pacific Northwest. The relative low cost and easy application of these membranes has lead to the widespread use in IRMA construction, both insulated and uninsulated, as well as for planters, fountains, and foundation walls.

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 (Figure 1). In some cases, large blisters (>2 in. deep) have displaced concrete pavers, creating hazardous walking conditions. As blisters expand over cracks or joints in the concrete, water can leak to the interior.

***Graham Finch** is a building science research engineer and **Brian Hubbs** is a senior building science specialist with RDH Building Engineering Ltd in Vancouver, BC. **Robert Bombino** is a senior building science specialist with RDH Building Sciences in Seattle, WA.*



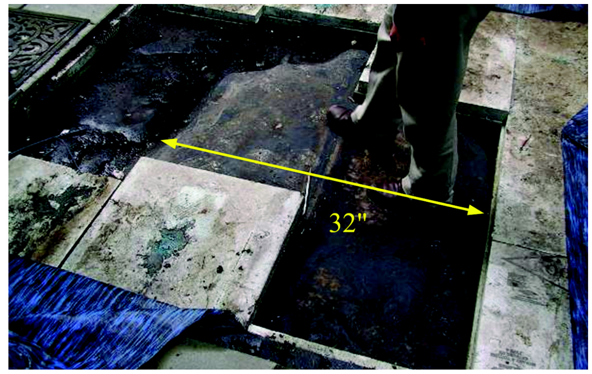


Figure 1 *Typical blistered roof membranes. Blister size ranges from penny-sized blisters to areas several square feet, membrane 5–10 years old.*

In our experience in the Pacific Northwest, the blisters described 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 installed over heated space) and ballast or other wearing course. In the wet Pacific Northwest climate, moisture remains in contact with the membrane for much of the year. Even in roofs with a positive drainage slope and drainage layer, water is sometimes found in contact with the membrane. We have further received numerous reports from other consultants and roofers in other wet locations in North America, Japan, and Europe who have observed similar blistering phenomena.

Research has shown that the moisture transport mechanism through these membranes is by osmosis through a semipermeable membrane (Finch et al. 2009). In light of this research, there is an interest from the construction community, including product manufacturers, to develop an industry-recognized (e.g., ASTM) test standard for osmotic flow through waterproofing membranes.

To date, there is no standard test method specifically designed to measure osmotic flow through waterproofing membranes. As part of our several years of researching this phenomenon, we have refined a proposed osmotic-flow test method, and have used this test to compile a small database of new and existing reference membranes with in-service blisters that we have tested. It is hoped that such a database of membrane types and in-situ field performance will lead to the ability to predict the durability of a particular membrane in service, and hopefully lead toward the development of new membranes that are impermeable to osmotic flow. Currently, the test allows comparison of the osmotic flow rates with other membranes that have and have not had a history of osmotic blistering.

TESTING PROTOCOL

It can be shown that two material properties are directly related to the osmotic flow potential of a waterproofing material over concrete within an inverted roofing assembly: inverted wet-cup vapor permeance and osmotic flow rate. Both of these properties would be measured as part of the proposed test standard using the methodology described below for each.

Inverted Wet-Cup Vapor Permeance

Inverted wet-cup vapor permeance indicates whether a waterproofing membrane may be susceptible to osmotic flow. The inverted wet-cup permeance value also provides a relative comparison to other membranes for which osmotic flow may or may not have been observed. Once a sufficient range of membranes with different chemistry and materials have been tested, it may be possible to correlate and use the inverted wet-cup permeance measurement to estimate an osmotic flow rate.

The reporting of dry- or even wet-cup permeance is not representative of the in-situ vapor permeance of waterproofing, which is exposed to liquid water and a high RH environment in an inverted roof assembly. The water vapor permeance of most liquid waterproofing materials tends to increase with RH and contact with water. Testing has shown that the permeance measured using an inverted wet-cup test can be up to 3.5 times higher than the dry-cup measurement and 1.5 times higher than the wet-cup measurement (see Figure 1, right side). Therefore, to report the correct permeance properties, waterproofing membranes manufacturers should test and report inverted wet cup values in technical literature.

In our experience, the application of primers or coatings to a membrane (in an attempt to represent the application of that primer to the substrate) will reduce its inverted wet-cup vapor permeance somewhat; however, testing for some membranes has found that a lower inverted wet-cup permeance (from the application of a 1–3 mil thick surface primer) does not necessarily result in a significantly lower osmotic

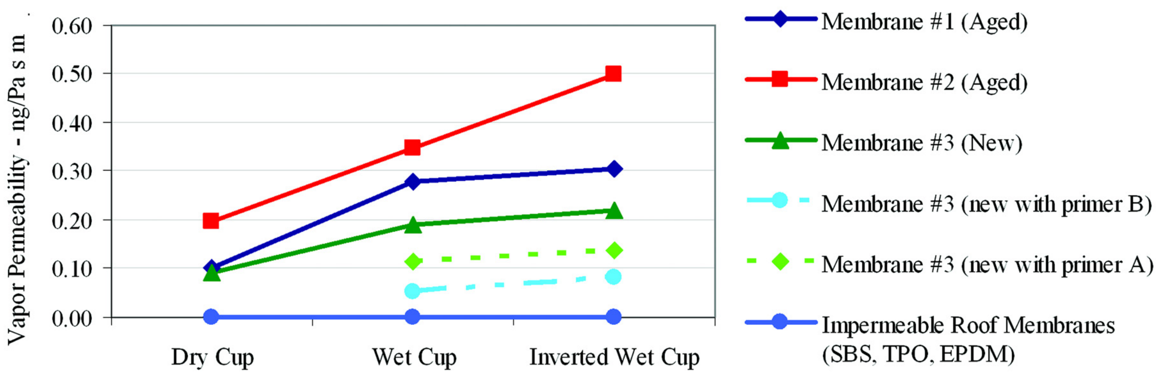


Figure 2 *Measured dry, wet, and inverted wet-cup vapor permeance for selected waterproofing membranes.*

flow rate. We have also found that aged samples (i.e., those installed on roofs for several years) had much higher permeance values than new samples, even of the same chemistry. This may be the result of prolonged exposure to moisture, swelling, organic deterioration, or exposure to an alkaline environment.

Osmotic Flow Rate

Direct measurement of the osmotic flow through a membrane using a standardized procedure indicates whether the membrane is susceptible to osmotic flow and potentially osmotic blistering. Blistering is the result of prolonged osmotic flow, often over a period of several years. It may be possible for a membrane to have a low osmotic flow rate but not be susceptible to blistering if the rate of osmotic flow is offset by drying from the concrete/membrane interface.

As no current apparatus exists to specifically measure osmotic flow, an apparatus was devised following several trials and development and used to measure the osmotic flow rates presented here.

Osmotic Flow

Osmosis is a naturally occurring phenomenon in which water flows through a semipermeable membrane from a solution of low salt concentration to a solution of high salt concentration, without the input of energy. Fresh water will flow through the membrane to the saltier side until equilibrium is achieved. Applying this to an inverted waterproofing application, the membrane separates rainwater from the concrete. Rainwater on top of the membrane behaves as a solution of low-salt concentration, whereas wet concrete behaves as a solution of high salt concentration. The concrete becomes wet by vapor diffusion and capillary flow through a permeable membrane or initial moisture within or on the surface of the concrete. This may be as small as liquid water within a surface void of the concrete. As demonstrated, asphalt-modified polyurethane waterproofing membranes are semipermeable to water vapor. These membranes also appear to be impermeable to the majority of salt and contaminant ions that create the osmotic cell.

Osmotic pressure is the pressure required to maintain equilibrium between the two sides, with no net movement of water. Typical osmotic pressures are in the kPa to MPa range, and have been calculated for salty water samples removed from site. While this high pressure could not have been physically contained within this elastic membrane, it is better visualized as a pressure potential that 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.

Osmotic pressure depends only on the molar concentration of the salt, not the type of salt present. Therefore, if any difference in salt content is present across a membrane, osmosis will occur. Initial testing indicates that the osmotic pressure caused by different molar concentrations of NaCl affects the osmotic flow rate through polyurethane membranes (Figure 3). In one trial experiment using severely blistered 30 mil aged membrane, a 1.0 molar (M) NaCl solution (55,000 kPa) resulted in a flow rate of 9.7 $g/m^2 \cdot day$, whereas a 0.1 M NaCl solution (460 kPa) resulted in only a slightly lower flow rate of 5.9 $g/m^2 \cdot day$ for an order of magnitude pressure difference.

A 0.1 M NaCl solution (460 kPa) resulted in only a slightly lower flow rate of 5.9 $g/m^2 \cdot day$ for an order of magnitude pressure difference. This large difference pressure and apparent restriction in flow rate may be explained by the effective pore size of the membrane and whether mass flow is dominated by Knudsen diffusion (in pores smaller than 0.05 μm) or molecular (Fickian) diffusion (in pores larger than 0.2 μm). For the nonporous waterproofing membranes tested here, Knudsen diffusion likely dominates. Since the osmotic pressure effect would only influence the molecular-diffusion portion of the water transport, the observed increase for an order of magnitude in osmotic potential implies the molecular diffusion component makes up only small portion of the transport mechanism (i.e., for this membrane, less than 10%).

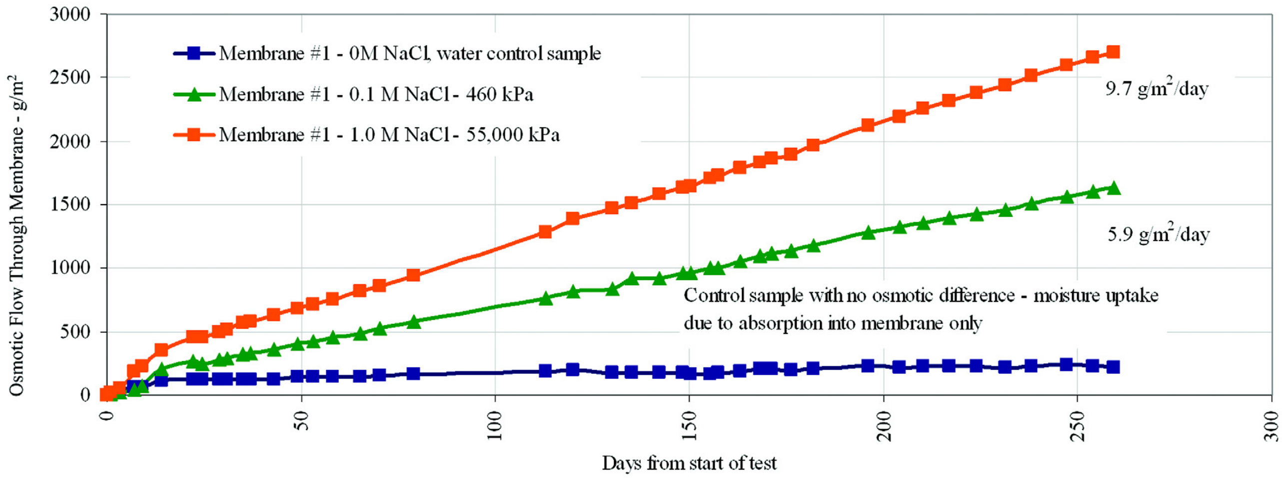


Figure 3 *Osmotic flow through membrane sample at 0.1 M and 1.0 M NaCl solution.*

In solutions containing multiple types of dissolved salts, the partial osmotic pressure for each is summed to determine the overall osmotic pressure. Reverse osmosis membrane manufacturers have simplified the formula to the following in terms of osmotic pressure π in psi to size reverse osmosis filtration systems (Lenntech 2008):

$$\pi = 1.12 \cdot T \cdot \sum m_j \tag{1}$$

where $\sum m_j$ is the sum of molality concentrations of all constituents in a solution (moles of solute/kg of solvent) and T is the absolute temperature in kelvins.

Testing for dissolved solids in water extracted from beneath osmosis-blistered membranes has found significant concentrations of sodium, potassium, silicon, and sulphate, mainly from the cement (calcium silicates $CaO{\bullet}SiO_2$), aggregates, mix water, and admixtures (e.g., fly ash, potash) present in the concrete.

Apparatus to Measure Osmotic Flow

To measure osmotic flow, an apparatus was designed to use the membrane to separate fresh and salty water with a known osmotic pressure potential. Various configurations of apparatus were tested during development, including tanks separated by membrane samples with pipettes to measure volumetric change; however, it was found that the simplest, most accurate, and most economical method of testing multiple membrane samples at once was to modify an inverted wet-cup container.

The osmotic flow apparatus consists of an open glass container with a known volume of salty water placed within it. A membrane sample is placed over the open end of the container and sealed on using a compression ring or open screw-top lid. The sealed container is then inverted and placed within a bath filled to an equal height with fresh water to remove any hydrostatic head difference between the liquids (Figure 4). The process of osmosis will result in a flow of water from the fresh to salty side of the membrane until, in theory, equilibrium is achieved. The apparatus was designed so the flow of water from fresh to salty side can be measured by the mass increase of the apparatus containing the salty water for several concurrent test specimens. By measuring the mass change of the container containing the salt water and membrane at regular intervals, the osmotic flow can be measured. In cases where osmotic flow is substantial, volumetric measurements can also be made.

For the majority of tests performed to date, the salt-water solution has consisted of a large sample of water removed from beneath the membrane of a severely blistered roof. The osmotic pressure as a result of the dissolved solids within liquid is in the order of 326 kPa and contained mainly sodium, potassium, and silicon, with a total dissolved solids concentration of ~3600 ppm. Further tests have also been performed with 0.1 M (460 kPa) and 1.0 M NaCl (55,000 kPa) solutions, and a standard salt concentration will be determined as part of the proposed test standard following further testing. It may be possible to accelerate the speed of testing using higher salt concentrations and osmotic pressures.

Procedure to Measure Osmotic Flow

A procedure is presented to assemble the apparatus and measure the osmotic flow rate through a cured membrane sample. Because the experiment can take up to 3–6 months to obtain useful data for some membranes, it is recommended that at least six identical samples plus three blank samples (deionized instead of salty water) to act as controls be prepared and tested simultaneously, in case a sample should leak or break during the experiment. Measuring multiple samples also allows for averaging, which has been found to be beneficial when dealing with cured liquid membranes prone to pinholes,

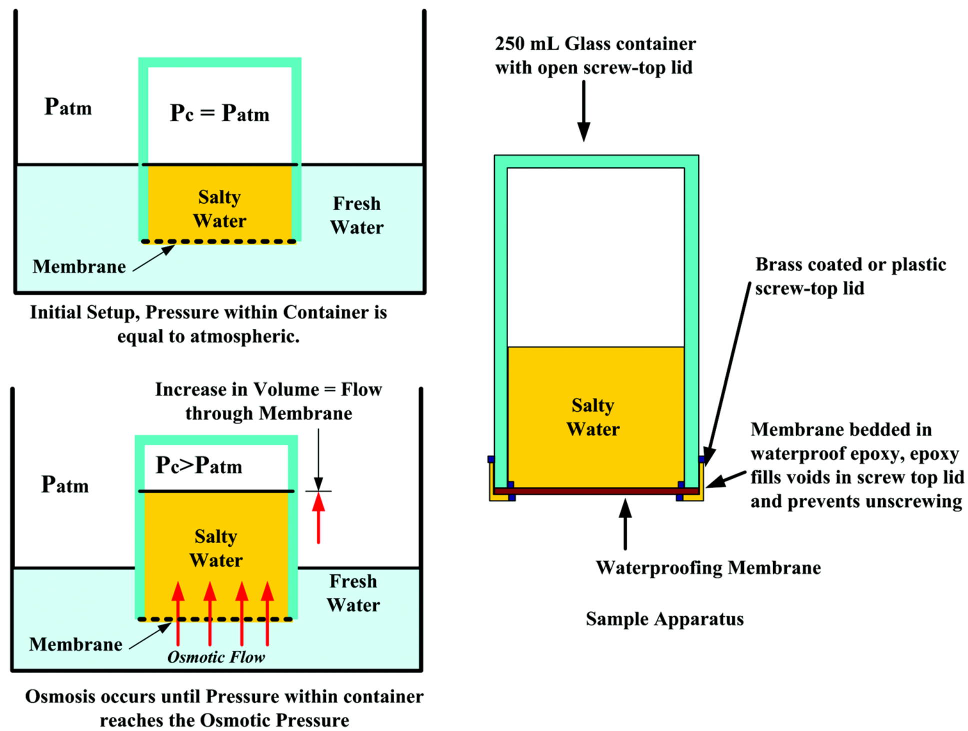


Figure 4 *Osmotic flow testing apparatus schematic.*

air voids, and thin/thick spots, all of which can affect the osmotic flow through the membrane.

1. Cut samples of membrane into circular discs to tightly fit within the open screw-top lid fitting. Initially weigh each membrane sample and then measure the thickness in at least 6 points to determine an average thickness. Note any surface voids, bubbles, or defects. Cut at least three membrane samples for test specimens plus three extra to be used for a moisture absorption test.
2. Apply waterproof (marine-grade) two-part epoxy to the perimeter of both sides of the membrane to create a sealed gasket between the lid and membrane and the lid and glass container. Epoxy is not required for most membranes, as the compression of the lid on the chamber creates a watertight seal; however, it is applied so the samples cannot be unscrewed accidentally. Plastic or stainless steel lids are recommended to avoid corrosion.
3. Prepare a salt-water solution consisting of 0.1 M NaCl (e.g., 5.8 g NaCl per liter of water).
4. Place a measured volume/mass of salt water into each of the test containers (six recommended) to fill the container to 1 in. Place a known mass of deionized water into each of the control containers (three recommended) in same manner.
5. After the epoxy gasket has cured, test the container for leaks and apply epoxy around the underside of the lid to create a watertight seal.
6. Measure and record the initial dry mass of each of the test and control samples.
7. Measure and record the initial dry mass of the samples cut for the moisture absorption test.
8. Optional: Perform an *ASTM Standard E96* inverted wet-cup test on the samples for 2–4 weeks, measuring the mass loss every 2–3 days to obtain sufficient and consistent readings. Alternatively, separate samples (at least three) may be prepared for this purpose to speed up the entire test.
9. Prepare a fresh-water bath using deionized water. Fill the water to a height so that any hydrostatic head is eliminated after the containers are placed within the bath. Using a stainless steel rack to lift the samples off the bottom of the container is recommended. Ensure any air bubbles are removed from the samples. Place moisture absorption uptake test specimens in bath.
10. At regular intervals (at least twice per week), remove all of the samples from the deionized water bath, and pat the surface dry using paper towels to remove any surface moisture. Weigh and record each sample and replace into deionized water bath. For samples with significant osmotic flow, the volumetric increase can also be

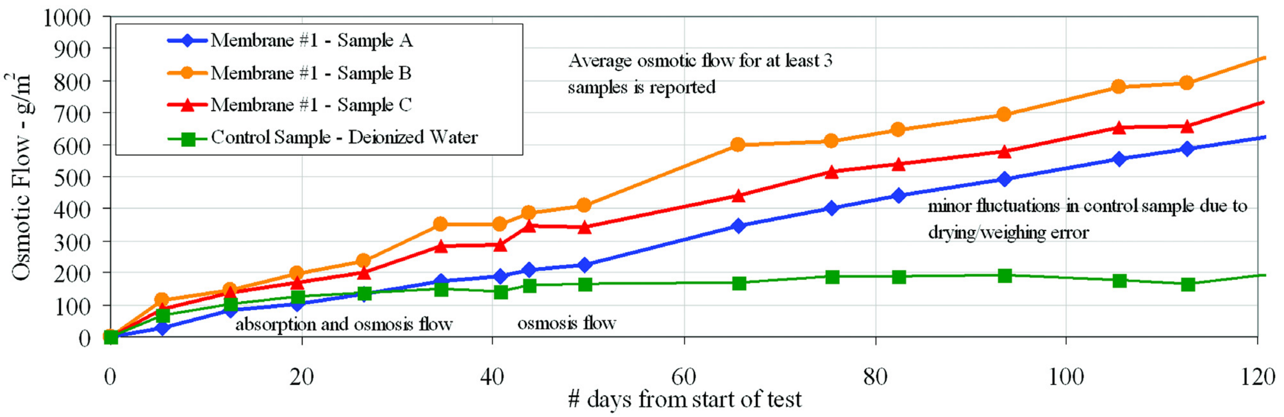


Figure 5 *Measured initial moisture uptake, absorption, and osmotic flow for three test samples and one control sample of membrane #1.*

measured using graduations on the sample container. Replace deionized water during each weighing.

11. The flow of water into (by absorption) and through the membrane (by osmosis) is measured by subtracting the sample mass from the initial dry mass. The flow of water should be reported in g/m^2 by dividing the mass increase by the area of exposed membrane (e.g., 0.14 g of water through a 0.0023 m^2 sample in a measurement time period of 7 days = 60.9 g/m^2 total, or 8.7 g/m^2/day).
12. Membrane disk samples cut for the absorption test and blank deionized water samples are measured to determine the moisture uptake into the membrane and when water absorption stops. The point at which absorption into the blank deionized water samples stops is the point at which the osmotic flow rate can be most accurately measured. From this point, at least 10 readings should be taken for at least one month. Data should be plotted to visually assess the osmotic flow rates.
13. The average osmotic flow rate can be determined by the average slope of the plotted line above the absorption/osmosis phase.

Sample test results for three test samples compared to a control (deionized water) sample of membrane #1 are presented in Figure 5, demonstrating the initial moisture uptake and later the measurable osmotic flow rate. The plot shows the moisture uptake for a common 30 mil membrane that demonstrated severe osmotic blistering in the field. Newer, less permeable membranes will take longer to fully adsorb moisture and for osmotic flow to be obvious.

RESULTS AND DISCUSSION

Measurements of Vapor Permeance and Osmotic Flow

To date, we have tested over a dozen different new and old membrane samples with varying inverted wet-cup vapor permeances and rates of osmotic flow. Aged samples were removed from buildings where blistering was observed, and new samples were prepared in a laboratory. Aged samples typically contain more voids, bubbles, and thickness irregularities in the membrane from the application to concrete slabs. Ranges of measured inverted wet-cup and osmotic flow results from the tests are presented in Table 1, and osmotic flow rates are plotted in Figure 6.

It should be noted that membrane #7 is the unaged version of membranes #2 and #3. Membranes #2 and #3 both failed by blistering in less than 5 to 10 years of service. The effects of long-term aging and exposure in the installed environment are unknown, but it appears that both osmosis and vapor permeance could increase with environmental exposure and age. Further research into the effects of aging is necessary to predicting long-term performance and resistance to osmotic blisters.

CONCLUSION AND RECOMMENDATIONS

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 demonstrate that the water-filled blisters can be explained by the fluid transfer mechanism of 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 apparatus and procedure presented can be used to measure osmotic flow rate through a membrane sample, typically in up to 3–6 months.

The rate of osmotic flow is a function of the vapor permeance of the membrane. Therefore, lowering the vapor permeability of the polyurethane membrane will likely reduce the potential for osmosis to start by reducing the potential for the

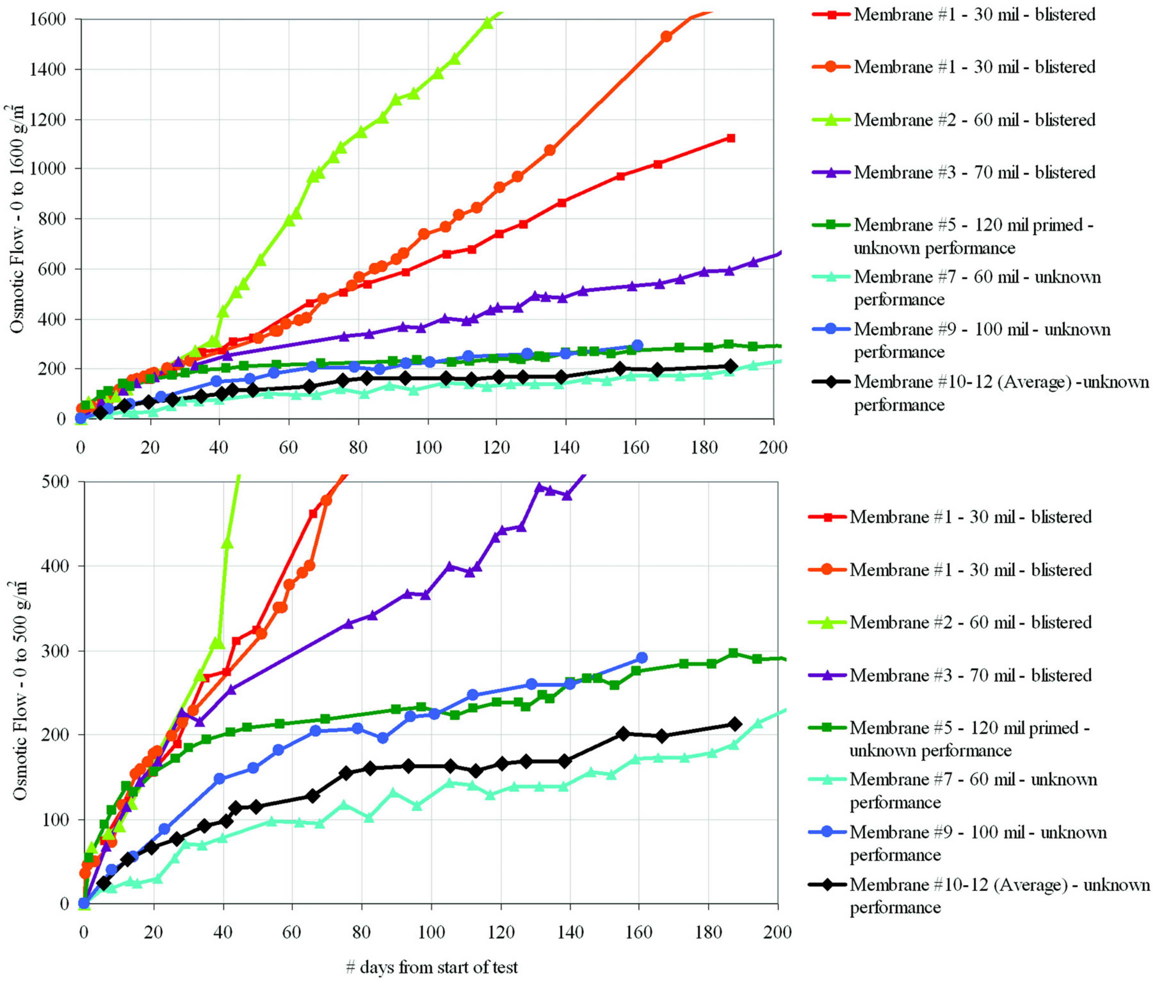


Figure 6 *Osmotic flow rates for eight different membrane samples (g/m²/day).*

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 semipermeable and have a vapor permeance ranging from 60 to 420 ng/Pa·s·m^2, depending on application thickness and chemical composition. Some new polyurethane membranes that also been tested have similar order of magnitude vapor permeance values (up to 120 ng/Pa·s·m^2), even when tested with certain concrete primers. Some products on the market are even marketed as "breathable" or more vapor-permeable for use on green concrete. This would not be a beneficial attribute long-term for a waterproofing membrane.

Osmotic flow rates measured through aged polyurethane membranes that were removed from blistered locations are on the order of 5 to 13 g/m^2/day. Testing has also been performed on new primed and unprimed polyurethane membranes that are currently available on the market, with measured flow rates of between 0.6 g/m^2·day to 3.1 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. As a minimum requirement, the membrane should have an inverted wet-cup vapor permeance of less than a concrete slab (range of 7 to 30 ng/Pa·s·m^2 for a 6 in. slab), and ideally closer to impermeable waterproofing/roofing membranes such as SBS, PVC, or EPDM (<1 ng/Pa·s·m^2).

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

Table 1. Summary of Measured Inverted Wet-Cup and Osmotic Flow Rates through Several Membranes

Membrane Sample Thickness and Condition	Osmotic Blisters Observed in Membrane in the Field?	Inverted Wet-Cup Vapor Permeance Range Measured, ng/Pa·s·m^2	Average Osmotic Flow* Range Measured, /m^2/day
#1: 30 mil aged	Yes	345 to 440	5.2 to 13.2
#2: 60 mil aged	Yes	200 to 430	8.1 to 13.2
#3: 70 mil aged	Yes	165 to 250	3.7 to 4.8
#4: 90 mil new, unprimed	Unknown, product is too new	70 to 120	1.7 to 3.1
#5: 90 mil new, epoxy primer	Unknown, product is too new	45 to 65	1.1 to 1.8
#6: 90 mil new, polyurethane primer	Unknown, product is too new	30	0.7 to 1.0
#7: 60 mil new, unprimed	Likely, chemistry same as membrane #2	65 to 75	0.8 to 1.7
#8: 60 mil new, with metal-flake coating	Likely, chemistry same as membrane #2	20	0.6 to 1.8
#9: 100 mil new, from building	Unknown, product is too new	70 to 75	0.8 to 1.1
#10: 150 mil new, unprimed	Unknown, product is too new	35	0.8 to 0.8
#11: 80 mil new, primed	Unknown, product is too new	30 to 50	0.7 to 0.9
#12: 100 mil new, primed	Unknown, product is too new	30 to 40	0.6 to 0.8

* Osmotic flow was measured using salty water removed from a membrane blister, osmotic pressure of ~326 kPa.

and the testing performed in this study, the existing standards do not have adequate test requirements to prevent premature blistering of polyurethane membranes. Therefore, we recommend including maximum allowable values for membrane vapor permeance, tested under inverted wet-cup conditions, and that osmosis testing requirements be included in current industry standards referenced by polyurethane membrane manufacturers, specifically *ASTM C836-00* and *CAN/CGSB–37.58-M86*.

This research leads toward an industry accepted test and standard that could be developed to test new IRMA roofing and waterproofing membranes for susceptibility to osmotic flow. Additional research is needed to determine allowable osmotic and vapor flow rates that can be safely accommodated by moisture flow through concrete slabs in service. 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 vapor 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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