Reducing the Risk of Moisture Problems From Concrete Roof Decks

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ABSTRACT

In recent years, the roofing industry has become increasingly aware of the problems caused by moisture in concrete roof decks that migrates into the roofing system. Installing a vapor retarder over the concrete deck is the primary method of addressing this problem. This paper summarizes some of the challenges associated with incorporating a vapor retarder into the roofing system. For example, selecting a vapor retarder of the appropriate vapor resistance is challenging due to the shortage of published data on the acceptable moisture limits of roofing materials. We explore the question of acceptable moisture limits through an extensive review of published literature, product-specific recommendations from manufacturers, and some preliminary laboratory testing of some common roof cover boards. This paper is based on the authors' experience as designers and investigators of roofing systems, literature review, and laboratory testing.

Photo 1 – Moisture-damaged gypsum cover board.

1. BACKGROUND

1.1 Consequences of Moisture

While the primary function of a roofing system is to prevent water from passing through it into the building or structure below, water or moisture vapor that collects within the roofing system can also be detrimental, both to the roofing system's immediate performance and its long-term durability. Besides leakage to the interior, moisture in roofing systems can have numerous negative consequences, including the following:

- Reduced thermal resistance of insulation
- Loss of strength of the insulation, coverboard (*Photos 1* and *2*), adhesive, or fasteners (*Photo 3*), leaving the roofing system vulnerable to uplift damage from wind or crushing from foot traffic or hail
- Deterioration of the structural deck
- Dimensional changes in the substrate, which can in turn damage the roof membrane
- Blistering or weakening of the roof membrane itself, especially with built-up roofing (BUR)
- Mold growth

1.2 Sources of Moisture

Moisture in the roofing system can come from a variety of sources, such as:

- Installation of wet materials (i.e.,

Photo 2 – Moisture-damaged fiberboard cover board.

Photo 3 – Corrosion of roofing fastener.

insulation that was not properly protected from weather while stored on site).

- Water leakage through the roof membrane, flashing, or adjacent construction
- Moisture vapor from interior humidity
    - — Moisture vapor from interior humidity may migrate into the roofing system by diffusion if no vapor retarder is installed. The need for a vapor retarder to limit the migration of interior moisture into the roofing system is generally acknowledged to depend on the local climate and the interior conditions of the building. Later sections of this paper include additional information about determining when a vapor retarder is needed.
    - — Moisture vapor from interior humidity may be carried into the roofing system by air leakage if there is no air barrier in the roofing system, particularly if the building is positively pressurized due to stack effect or the operation of the HVAC system. This is generally addressed by including an air barrier in the roofing system and connecting it to the air barrier in the wall system to provide a continuous barrier.
- When a new concrete deck is poured, some of the mix water is used up in chemical reactions as the concrete cures, and some evaporates; but the rate of evaporation is slow, so large quantities of water remain stored within the pore structure of the concrete for extended periods of time. While the concrete itself is generally not damaged by this moisture, the moisture may migrate into the roofing system, where it is absorbed by materials that are more sensitive to moisture. Historically, roofing systems were adhered to concrete decks in hot asphalt; the hot asphalt (often with reinforcing felts) provided the additional benefit of limiting the rate of moisture migration from the concrete into the roofing system. However, modern single-ply roofing systems are often installed today without any vapor retarder on the concrete deck.

Comparison can be made to the

> flooring industry, which has also suffered detrimental effects from moisture diffusing out of concrete and, as a result, has developed consensus test methods for measuring the internal relative humidity (RH) of concrete or moisture evaporating out of concrete. Flooring manufacturers typically specify acceptable RH or moisture vapor emission limits for the concrete as a condition of their warranties. By contrast, the roofing industry, while it has begun to focus more attention on this issue,[1] had not, as of 2011, "established any benchmarks or acceptance levels" for moisture in concrete.[2]

A 2012 research update[3] proposes that "Until we have more data, 75% relative humidity appears appropriate for normal-weight concrete" and recommends monitoring the RH of concrete according to ASTM F2170[4] to determine when it is "dry" enough to roof over.

However, one limitation of F2170 testing is that the standard requires conditioning both the concrete slab and the air above it to a constant "service temperature" and relative humidity for at least 48 hours before making measurements. But constant temperature and RH do not exist for an in-service roof; the conditions vary constantly with the weather. Furthermore, the effect that concrete moisture has on the roofing system will depend on the specifics of the roofing system and the local climate, so it may be difficult to establish an industry-wide "acceptable" level of moisture for all concrete roof decks.

Another recent study[5] found that concrete retains significant amounts of water after months of drying; therefore, high moisture levels are likely to still be present when the roofing system is installed. In most roofing installations, it is impractical to wait for the concrete deck to "dry" fully; it is often faster and more reliable to install a vapor retarder over the concrete deck to inhibit the migration of moisture from the concrete into the roofing system. Specifying the vapor retarder presents several challenges as discussed in the next section.

2. VAPOR RETARDER CHALLENGES

2.1 Wind Uplift Rating

In many roofing systems installed over concrete decks, the roof insulation is adhered to the concrete (often with ribbons of low-rise foam adhesive). Incorporating a vapor retarder into the system means adding another layer that needs to be adhered to the concrete and to which the insulation needs to be adhered. In this situation, the vapor retarder can affect the wind uplift resistance, so it is crucial that the vapor retarder be part of the tested assembly.

Most roofing system manufacturers now offer tested assemblies that include adhered vapor retarders, but the relative number of options for this system is more limited than those without a vapor retarder. Recent searches of FM Global's RoofNav online database[6] found that there are 2.5 to 3 times fewer tested systems with a vapor retarder than the number of systems without a vapor retarder. These searches included both adhered and mechanically attached insulation systems. In the authors' experience, roofing system designs with adhered insulation and a vapor retarder have even fewer options.

If the vapor retarder is going to be adhered, moisture in the concrete deck can affect the adhesion, so the question of acceptable moisture content in the concrete deck still must be addressed. Similar to adhering a plaza waterproofing membrane or deck coating to concrete, it is advisable to contact the manufacturer for recommendations and use a mock-up as the final criteria for evaluating whether good adhesion can be achieved.

Fortunately, designers have other options besides adhesive for securing roof insulation. Roof insulation (or membranes) can be mechanically attached through the vapor retarder into the concrete deck, which avoids the difficulty in finding a tested system that relies on adhesion of (and to) the vapor retarder. Alternatively, roofing systems in some regions can be ballasted; however, building codes prohibit stone ballast in some high-wind regions.

2.2. Product Selection

Another challenge is determining the appropriate vapor permeance for the vapor retarder. Some designers rely on past experience and rules of thumb or the minimum requirements of the building code, while others use moisture vapor transmission calculations to predict the in-service moisture contents of any moisture-sensitive materials in the roofing system. Rules of thumb and calculations are discussed in more detail below.

2.2.1 Rules of Thumb

One rule of thumb[7] that is sometimes used is that every layer in the system should be ten times more permeable than the vapor retarder to avoid creating a vapor trap. *Table 1* lists the typical range of permeance of some common roof membranes and vapor retarders. Because of the low permeance of most roof membranes, using a vapor retarder often violates the rule of thumb for avoiding a vapor trap. This means many roofing systems have very limited ability to self-dry any water that leaks through the membrane. Even a small membrane defect that may not produce a large enough volume of leakage to appear on the inside of the building can cause water to accumulate in the roofing system over time and result in concealed damage. Desjarlais explains the disadvantages of compact roofs in several of his publications[8,9,10] and recommends avoiding vapor retarders where they can be shown to be unnecessary. However, in many cases—including new construction with concrete decks—vapor retarders have been shown to be necessary.[11]

2.2.2 Moisture Vapor Transmission Calculations

Calculations provide a more sophisticated analysis than simple rules of thumb, but they also have their own challenges.

Moisture moves between components of the roofing system by diffusion over time. The moisture content of a particular layer may vary with daily or seasonal weather variations, and there may be a net wetting or drying over the long term (multiple years).

The construction industry has been developing and publishing methods for evaluating moisture vapor flow for many years. Hand calculation methods developed specifically for the roofing industry include two published in 1980[15] and another in 1989[16]; other criteria exist in ASHRAE and NRCA publications. In the past two decades, exponential increases in available computing power have made state-of-the-art computer programs for predicting moisture vapor flow (e.g., MOIST and WUFI) readily available. These programs have made moisture vapor transport easier to quantify and are more accurate than previous hand calculations. These state-of-the-art computer programs are now in widespread use by building envelope consultants.

WUFI,[17] a computer program by the Fraunhofer Institute for Building Physics (Germany), calculates transient one-

Material	Thickness (mils 0.001 in.)	Permeance (U.S. perms) ASTM E96 Procedure B[12]	Sources[13]
Roof Membranes			
BUR	Not reported	0.000	ASHRAE[14]
EPDM	60 mils	0.030 - 0.040	2 manufacturers
PVC	60 mils	0.050 - 0.220	4 manufacturers
TPO	60 mils	0.010 - 0.050	3 manufacturers
Vapor Retarders – Loose-Laid			
Polyethylene or “polyolefin” sheet – various grades	6 mils	0.059 - 0.130	2 manufacturers
	7-8 mils	0.038	1 manufacturer
	10 mils	0.019 - 0.039	3 manufacturers
	15 mils	0.009 - 0.021	2 manufacturers
Polyolefin – aluminum composite	14-15 mils total	0.000	1 manufacturer
Vapor Retarders – Self-Adhered			
Polyolefin – bituminous composite	32 mils total	.017	2 manufacturers

Table 1 – Permeance of selected roof membranes and vapor retarders.

dimensional heat and moisture transport and can be used to quantitatively predict how moisture levels within a building envelope assembly vary over time. WUFI uses historical, hourly weather data for user-selected project locations to simulate time-varying exterior conditions (temperature, RH, solar exposure, etc.) during the course of the simulation. An example output screenshot is shown in *Figure 1*.

WUFI can also simulate several years of moisture migration to analyze seasonal variations and year-to-year cumulative wetting and drying trends. The output data can be easily reviewed to determine, for each layer in the roofing system, moisture-related data such as (1) maximum annual moisture content, (2) quantities of condensate (if any), (3) number of occurrences of moisture content exceeding established thresholds, and (4) number of freeze-thaw cycles.

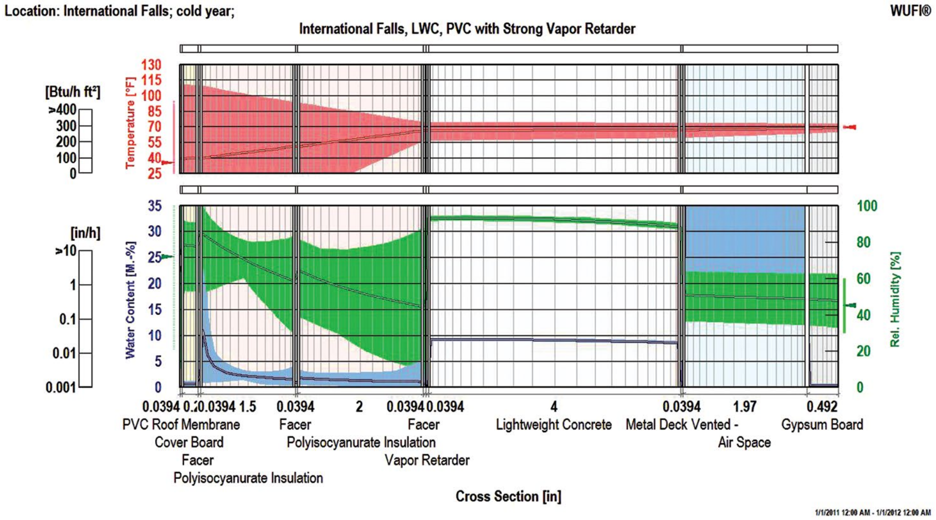

Figure 1 – Example WUFI simulation screenshot for a roofing system, showing the results for a typical year in International Falls, MN. The physical layers of the roofing system from top (exterior) to bottom (interior) are listed from left to right. The shading in the top panel indicates the range of service temperatures. The lower shaded areas indicate the ranges of relative humidity and water content.

A recent study[18] used WUFI to analyze a variety of roofing systems in a variety of U.S. climates and found that in new construction, all roofing systems constructed over cast-in-place concrete decks accumulated problematic levels of moisture within the roofing system unless a vapor retarder was included. The study further found that selection of an effective vapor retarder depends on the roof membrane; on typical buildings, the vapor retarder should have a lower permeance than the roof membrane. The selection of an effective vapor retarder also depends on the local climate; the study "did not find systems that perform equally in all climates[, and]...each geographical location required some fine-tuning of the roof system to make it work."

One limitation of WUFI analysis is that it focuses on vapor diffusion and generally does not account for bulk air or water leakage; therefore, the accuracy of the results depends on proper functioning of the roof membrane and air barrier. Also, interpretation of WUFI results requires knowledge or assumptions regarding the acceptable moisture limits of the materials being considered. The study recommends more research "to determine the maximum amount of moisture that roofing materials can safely tolerate." Quantitative knowledge of moisture content and acceptable moisture limits would also be valuable when one is asked to evaluate existing roofs to determine whether problematic levels of moisture are present.

3. ACCEPTABLE MOISTURE CONTENT OF ROOFING MATERIALS

Several industry sources have recognized the need for more research to determine acceptable moisture limits for roofing materials. The recommendation in the concrete moisture study discussed in the previous section echoes an earlier recommendation by Kyle and Desjarlais[19] that "researchers must establish a set of moisture limits with a reasonable safety factor by means of well-controlled experiments." This need was discussed even earlier by Tobiasson,[20] who stated, "For most roofs in most locations, the objective is to limit seasonal wetting to an acceptable level. This level will vary with the moisture sensitivity of the materials present. ...However, developing moisture limit states for each of the myriad roofing systems on the market is a sizable task that has not yet been accomplished." Kirby[21] similarly concluded that "the roofing industry does not have a consensus evaluation method for determining whether insulation is wet."

This section discusses information on acceptable moisture limits for roofing materials based on three sources: (1) limits proposed in industry publications, (2) manufacturers' recommendations, and (3) recent laboratory testing conducted in support of this paper.

3.1 Industry Publications

A wide variety of information and opinions on acceptable moisture content is available, illustrating the lack of consensus. We reviewed technical literature spanning the past 35 years and found several conflicting theories regarding acceptable moisture limits in roofing materials. The theories for acceptable moisture limits discussed below are generally listed in order of least stringent to most stringent, although there is ambiguity in some of the criteria.

- **Thermal resistance ratio (TRR) 80% maximum.** The thermal resistivity (R-value) of insulation is reduced when it becomes wet. In 1991, researchers at the U.S. Army Corps of Engineers' Cold Regions Research and Engineering Laboratory (CRREL)[22] proposed the following criterion: "The ratio of a material's wet thermal resistivity to its dry thermal resistivity is termed its TRR. ...Insulation with a TRR of 80 percent or less is, by our definition, 'wet' and unacceptable." The paper acknowledges that, "For some insulations, less moisture than that required to reduce the TRR below 80 percent can be detrimental for other reasons (e.g., delamination, rot, and corrosion of fasteners). It is not yet known what those moisture 'limit states' should be. ...As additional information on other moisture 'limit states' becomes available, it is expected that maximum acceptable moisture contents for some materials will decrease below the 80-percent TRR values." The paper further acknowledges that equilibrium moisture content (EMC), discussed below, is a more appropriate pass/fail criterion for new materials to be installed; TRR is proposed primarily for deciding when to replace existing insulation. *Table 2* summarizes some the EMC and TRR data for some other insulation products still in use today.
- **Seasonal wetting of 1-2% by volume.**[23] For foam insulation with 2-pcf density, this equates to 31-62% moisture content when calculated as a percent of dry weight.
- **No visible liquid water.** Kirby[24] states, "One factor can never be ignored: If liquid moisture is present in existing insulation, the insulation is too wet to be left in place or re-covered."

- **Only small amounts of condensation.** Tobiasson[25] stated, “A small amount of moisture may condense, then, without doing any real harm.” He also stated, “A little condensation on the coldest day of the winter will do no harm, but when condensation occurs for many days, weeks, or months, the amount of moisture deposited can create major problems.”[26] Condren took a similar approach but quantified his acceptable “small amount” of condensation, proposing a limit of no condensation deeper than 1/16 in. or 1/32 in. below the membrane, depending on the substrate material.[27] Desjarlais and Karagiozis[28] base their analysis on the criterion that the insulation should not have an RH of 100% (i.e., condensation occurring) for more than 24 hours, which is consistent with one of the three criteria in ASHRAE 160 (discussed below).
- **No condensation.** Desjarlais and Byars[29] contend that “moisture accumulation in a roof system must not be large enough to cause condensation within the roof, since this can damage the insulation and reduce its effectiveness.” They also state that “moisture accumulation should not be great enough to cause degradation of the insulation material or membrane. To pass this requirement, there must be no condensation under the roof membrane.”
- **EMC 40%, 45%, or 90% maximum.** The concept of EMC as a metric for determining acceptable moisture levels in roofing materials was first proposed in a 1977 paper[30] regarding roofing felts, but later expanded to include insulation and other materials. The 1977 paper proposed 40% EMC as the limit for roofing felts that were sufficiently dry to avoid the appearance of blisters when hot asphalt is applied to the felts in construction of a built-up roofing membrane. In addition to the blistering concerns, the 1977 paper found that conditioning organic and coated organic roofing felts in a moist environment reduced their tensile strength (compared to oven-dried samples) by 6-18% when conditioned at 40% RH for six weeks, and by 11-38% when conditioned at 90% RH for nine weeks. The effects of moisture on roofing felts were also studied by several other researchers around the same time.[31] The 1977 paper also examined the EMC of insulation materials, and notes, “The test results do not allow definite conclusions as to the ‘tolerable’ moisture level of the insulations. However, we expect any ‘excess’ moisture in the insulation to be available to influence the roofing membrane. …In view of our field experience and pending further research results, it seems prudent to assume that insulation moisture will not damage the system if the moisture does not exceed the equilibrium moisture content attained by 40% RH storage.”

  A 1985 article[32] provides EMC for various roofing materials conditioned at 20°C (68°F) and both 45% and 90% RH. The article notes, “When the material contains more water than its EMC, it is wet and may donate water to surrounding air or materials.” The EMCs for unfaced polyisocyanurate insulation were updated in 2003.[33] EMCs for selected products that are still in use today are summarized in *Table 2*, along with TRR data.

  A material that contains less than 45% EMC is considered dry; between 45% EMC and 90% EMC is considered moist; and over 90% EMC is considered wet.
- **Avoid three conditions favorable to mold growth.** There is broad consensus that mold growth should be avoided in buildings due to potential health impacts and because mold growth implies at least some level of decay. The International Energy Agency (IEA)[36] states that susceptible surfaces are in danger of developing mold growth if the relative humidity at the surface rises above 80% RH for a sustained period of several days.

  Temperature also plays a role. Below 32°F, fungal cells may survive but rarely grow; and above 104°F, most cells stop growing and soon die. ASHRAE 160[37] is generally consistent with IEA but provides more specific recommendations. ASHRAE recommends avoiding the following humidity conditions in order to minimize problems associated with mold growth on surfaces of components of building envelope assemblies; these criteria apply when the running

Material	EMC, Mass % @ 20°C[34]		Moisture content, Mass % @ 80% TRR[35]
	45% RH	90% RH	
Faced Polyisocyanurate	1.1	2.9	
Unfaced Polyisocyanurate	1.7	5	262
Expanded Polystyrene (1 pcf)	1.9	2	383
Extruded Polystyrene	0.5	0.8	185
Perlite Board	1.7	5	17
Wood Fiberboard	5.4	15	15
Gypsum	0.4	0.6	8
D226 Asphalt - Organic Felt	4.1 - 4.3	7.9 - 8.2	
D2178 Glass Felt	0.5 - 0.9	0.6 - 1.1	

Table 2 – EMC and TRR of selected roofing materials.

average surface temperature (for the duration of interest) is between 41°F and 104°F:

- 30-day running average surface RH ≥ 80%
- 7-day running average surface RH ≥ 98%
- 24-hr running average surface RH = 100%

In summary, a wide range of theories has been proposed regarding acceptable moisture limits in roofing materials. Most past physical testing on the effects of moisture on roofing materials has focused on two issues: (1) loss of thermal resistance of insulation, and (2) weakening, decay, and dimensional instability of built-up roofing.

In our experience, loss of strength of the insulation (or its facers) and cover board are also significant concerns, because they affect the ability of the roofing system to resist common loads such as foot traffic, hail, or wind uplift. Moisture-induced degradation of water-based membrane bonding adhesive has also been reported.[38]

However, we are not aware of any industry publications containing data on how moisture affects the strength of insulation, cover boards, or bonding adhesive, with the exception of some limited data on gypsum cover boards discussed in the next section.

3.2 Product-Specific Manufacturer Recommendations

We contacted manufacturers of polyisocyanurate insulation and gypsum cover boards to ask for recommendations on acceptable in-service moisture limits for their products. This section summarizes the information provided by manufacturers.

3.2.1 Polyisocyanurate Insulation

We contacted four manufacturers of polyisocyanurate roof insulation and inquired about acceptable in-service moisture limits. One manufacturer was unresponsive, and two said they do not have any data or recommendations. The fourth manufacturer cited 3% moisture content as a rule of thumb but did not provide any supporting data.[39]

3.2.2 Gypsum Cover Boards

A 2001 article[40] provides data on the water absorption of a gypsum cover board product after 24 hours of conditioning at 95% RH, two hours of exposure to surface moisture, two hours of immersion, and 24 hours of immersion. The article also provides peel adhesion data for hot asphalt application to boards at ambient conditions and after seven days at 95% RH. The article does not provide any recommendations for acceptable moisture limits; its main focus is on avoiding heat damage to the gypsum during installation of roofing membranes set in hot asphalt or torch application.

In addition, we contacted two manufacturers of gypsum cover boards and inquired about acceptable in-service moisture limits. One manufacturer stated that it manufactures its gypsum board to less than 2% free water and recommends that its product does not become “wet” but could not define what moisture content it considers to be “wet” or provide any recommendations for in-service moisture limits.[41] The other manufacturer stated that its product often has less than 1% free water as delivered from the factory, and cited a variety of thresholds of concern for moisture content in service, including 2%, 4%, and 5% but did not provide clear recommendations for an acceptable level for long-term performance.[42] Also, the manufacturer did not provide any supporting data on the strength of its material at those moisture levels.

In summary, very little information is available from manufacturers of roofing materials regarding their products’ resistance to moisture degradation.

3.3 Laboratory Testing

To collect some initial data on the moisture resistance of roofing materials, we selected three insulation cover board products for testing. Two of the products are gypsum-based, the third is high-density polyisocyanurate, and all are nominally ½ in. thick. Insulation and bonding adhesive are also of interest, but are excluded from this initial testing.

3.3.1 Description of Testing Program

We exposed the samples to a variety of moisture conditions and tested their flexural strength. Flexural strength is relevant to

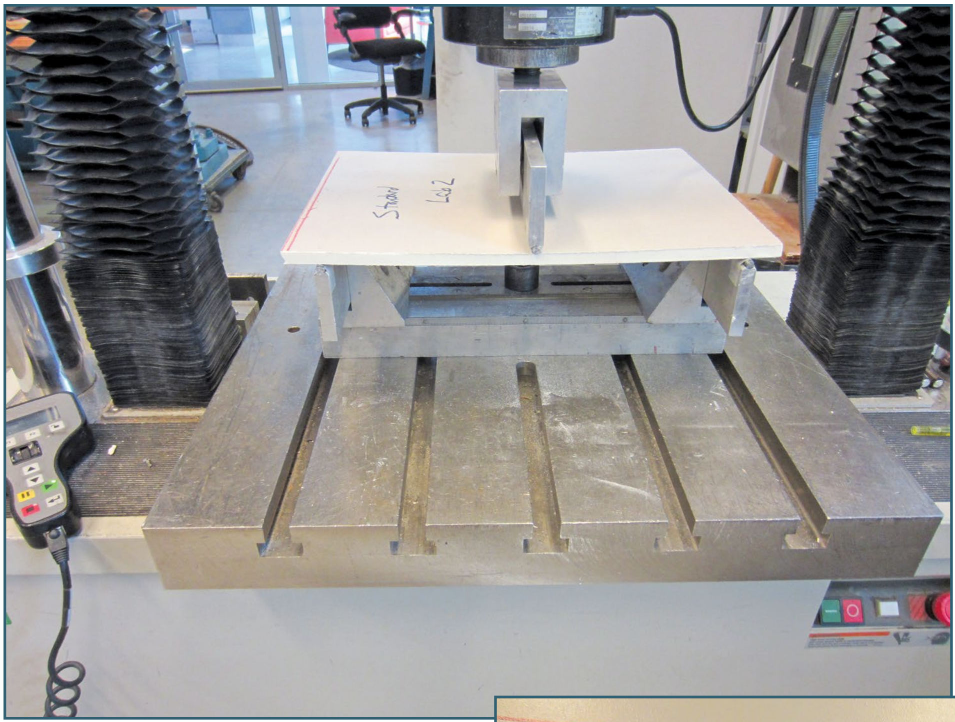

Photo 4 – Flexural test setup.

Photo 5 – Flexural test in progress.

the wind uplift resistance of intermittently attached cover boards. Tensile strength and compressive strength perpendicular to the plane of the board are also of interest; these properties are excluded from this initial testing but should be considered in future testing.

Three samples of each of the three products were exposed to each of the following ten different moisture conditions (90 samples total):

- Oven drying at 100°F (below the 110 to 115°F maximum recommended by one of the gypsum manufacturers)
- Standard laboratory conditions (50% RH and 74°F)
- High humidity (95% RH and 74°F)
- High humidity (95% RH and 74°F) followed by oven drying
- Water immersion for 30 minutes
- Water immersion for 30 minutes followed by oven drying
- Water immersion for 1 hour
- Water immersion for 1 hour followed by oven drying
- Water immersion for 24 hours
- Water immersion for 24 hours followed by oven drying

After conditioning, we tested the flexural strength of the samples according to modified ASTM C473[43] method B. The test procedure generally followed C473, but the sampling procedures and the definition of breaking load were modified to suit the goals and scope of our test program. Our test method is briefly summarized as follows and is depicted in *Photos 4* and *5*:

- Samples were cut to 12 x 16 in., with the 16-in. dimension parallel to the long dimension of the board. Some samples included the factory edge of the board. All samples were tested face up.
- The flexure fixture was set up with supports at a 14-in. span and a center-loading nose.
- Load was applied at a constant crosshead rate of 1 in./minute until the load resistance of the sample decreased; the maximum load was reported.

The polyisocyanurate board has anomalies in the foam structure, known as "knit lines," where the ribbons of foam came together during the manufacturing process. The knit lines are parallel to the long dimension of the board. By testing only samples spanning parallel to the knit lines, we avoided testing the weaker orientation.

3.3.2 Results

The results of our testing are summa-

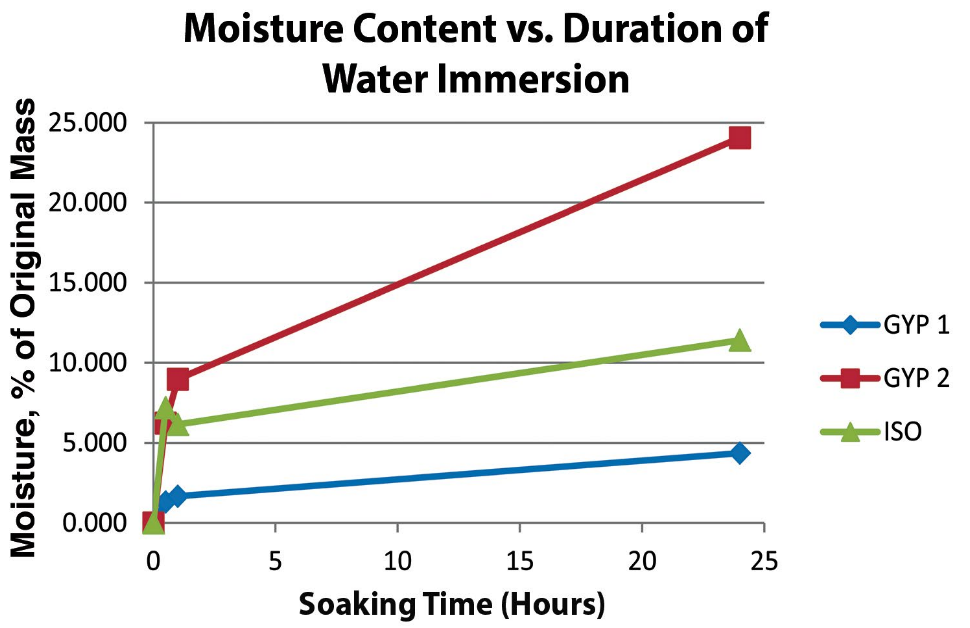

Figure 2 – Moisture content (% of original mass) vs. duration of water immersion (hours) for three cover board products. Each data point indicates an average of three or more samples.

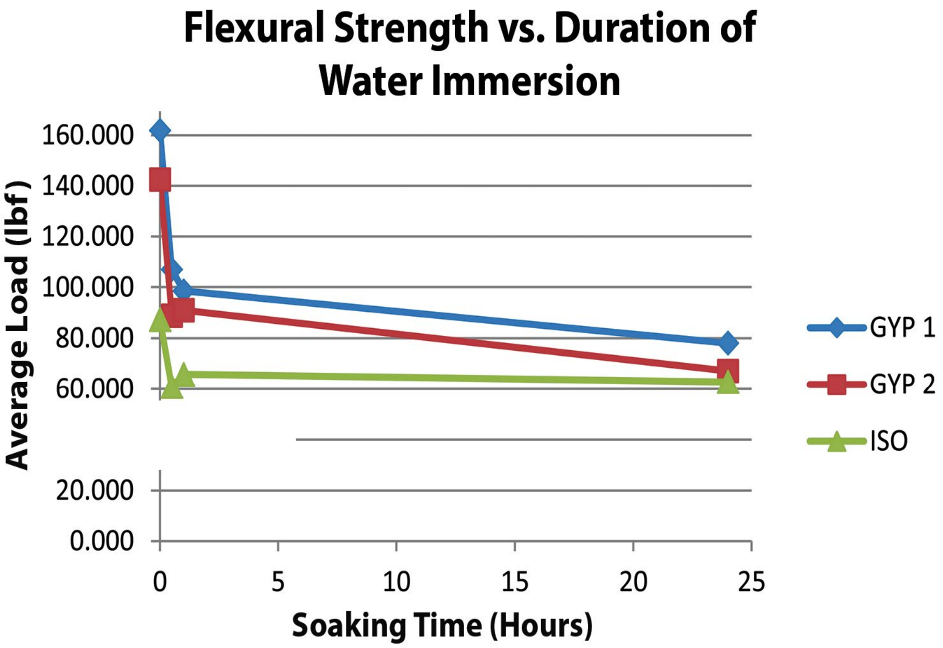

Figure 3 – Flexural strength (lbs.) vs. duration of water immersion (hours) for three cover board products. Each data point indicates an average of three or more samples.

rized as follows. We refer to the two gypsum products as "GYP #1" and "GYP #2," and the polyisocyanurate product as "ISO." Our test results are not suitable for design-strength values; our testing was intended only to explore the trends of strength loss caused by exposure to moisture.

Moisture conditioning had the following effects on the flexural strength:

- **50% RH –** None of the three products was significantly weakened by conditioning to standard laboratory conditions (50% RH) compared to oven-dry conditions.
- **95% RH –** The ISO was unaffected at 95% RH, but the two gypsum products lost some strength. GYP #1 was reduced to 70% of its standard laboratory strength, and GYP #2 was reduced to 80%.
- **Water immersion –** The three products showed differing rates of water absorption when immersed. After 24 hours, GYP #1 had gained 4% weight, GYP #2 had gained 24% weight, and ISO had gained 11% weight (*Figure 2*). All three products rapidly lost strength when immersed in water (*Figure 3*). Most of the strength loss occurred in the first hour of immersion. In the first hour, the two gypsum products were reduced to approximately 60% of their standard laboratory strength, and ISO was reduced to approximately 70% of its standard laboratory strength. The rate of loss slowed significantly after one hour of immersion; at 24 hours, the two gypsum products retained approximately 50% of their standard laboratory strength, and ISO retained around 70%.
- **Moisture content –** When we plot strength versus moisture content rather than wetting time (*Figure 4*), we see that the most dramatic strength loss occurs in the range of 0 to 3% moisture content by weight. We also see more of a difference among the three products. At 6% moisture content, GYP #1 is reduced to approximately 45% of its standard laboratory strength, GYP #2 is reduced to approximately 63%, and ISO to 73%.
- **Oven drying after wetting –** All three products regained all of their original strength (to within the level of accuracy of the test method) when oven dried after one wetting cycle.

3.3.3 Discussion of Test Results

Our testing showed that some common cover board products lose strength quickly and at relatively low moisture contents (less than 5% by mass) when wetted. This result is consistent with our field observations on existing roofs with wet cover boards and is also consistent with statements from one gypsum board manufacturer that moisture content over 2-5% is a concern.

The polyisocyanurate product was less affected by moisture than the two gypsum products.

Our testing further showed that some common cover board products exposed to one relatively short wetting cycle will regain virtually all of their original strength after oven drying. While this result supports the concept that a small amount of short-term condensation may be acceptable in some circumstances, it does not provide sufficient data to define those acceptable circumstances. On many roofs, the wetting is longer term, and the drying is less complete than in our tests. In addition to longer-duration wetting, other factors that could result in unacceptable strength loss in cover boards include: (1) a greater number of wetting and drying cycles, (2) freeze-thaw cycles, which are common because the coldest weather coincides with the peak moisture levels directly under the roofing membrane, and (3) loading from wind or foot traffic during one of the wetting cycles when the materials are temporarily weakened may result in permanent strength loss or even immediate failure. There is no guarantee that loading will occur only when the materials are dry and at their maximum strength.

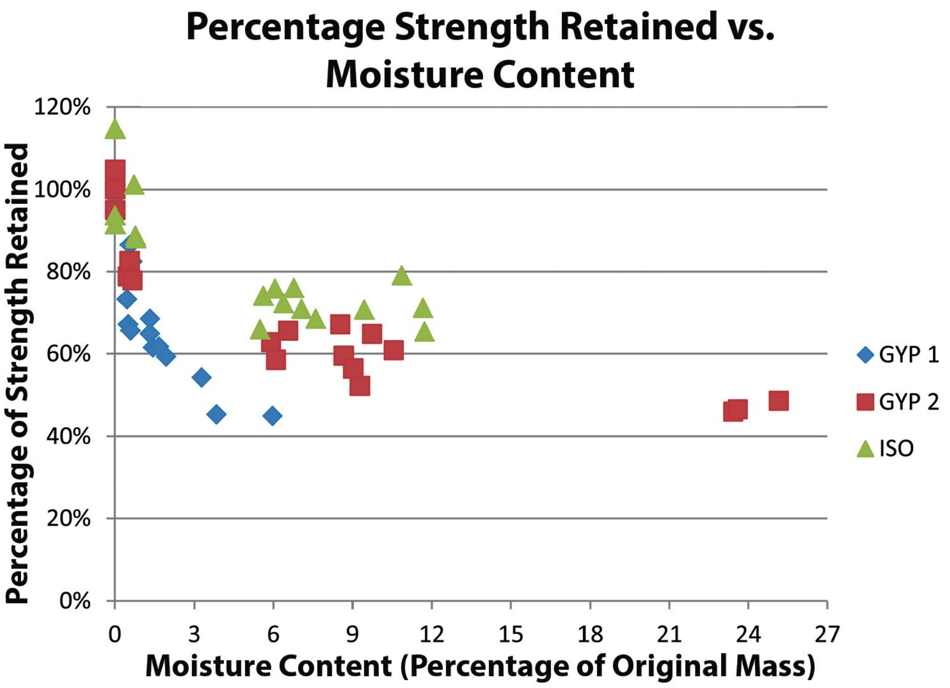

Figure 4 – Percent of original flexural strength retained vs. moisture content (% of original mass) for three cover board products. Each data point indicates one sample.

4. CONCLUSIONS AND RECOMMENDATIONS

We conclude the following regarding roofing system design for moisture in concrete decks:

- Most roofs on new concrete decks need vapor retarders. This poses some challenges with wind uplift rating and product selection, but these challenges can be addressed through careful design. As additional roofing systems that include an adhered vapor retarder are developed and tested for wind uplift, designers will gain more flexibility.
- State-of-the-art analysis tools are available to predict time-varying moisture levels due to vapor migration through the roofing system and assist selecting an appropriate vapor retarder. Interpreting the results of these analyses requires knowledge of the acceptable in-service moisture limits of roofing materials.

We conclude the following regarding acceptable in-service moisture limits:

- Prior publications have proposed various acceptance criteria for moisture content of roofing materials. An industry consensus does not exist, and product-specific data and recommendations from manufacturers are lacking.
- Our test data show that some common cover board products lose strength quickly and at relatively low moisture contents (less than 5% by mass) when wetted. However, our data are insufficient to establish acceptable moisture levels.
- We recommend additional research into the acceptable in-service moisture limits of roofing materials. In the interim and until additional data become available, roofing professionals will have to continue to rely on their experience and judgment.

ACKNOWLEDGMENTS

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The authors would also like to acknowledge the significant contributions made by Stephen Condren, Joseph Piñon, and Paul Scheiner in their August 2012 work referenced in this paper. Their work has lent much-needed clarity to the issue of moisture in concrete roof decks, and provided a clear direction for future research needs.

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FOOTNOTES

1. Mark S. Graham, "Moisture in Concrete Roof Decks," *Professional Roofing*, February 2010.
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Engineer Charged With Negligence in Mall Roof Collapse

The engineer who declared that a mall was safe two days before its roof collapsed, killing two, has been charged with three counts of criminal negligence. Robert Wood, 64, former president of M.R. Wright & Assoc. Inc., Sault Sainte Marie, Ontario, had inspected the Algo Centre Mall in Elliot Lake, Ontario, just prior to its collapse in June 2012.

A judicial inquiry heard that the roof of the poorly designed structure leaked from the time of its construction, and decades of water and salt penetration caused severe rusting of the steel support structure. In a 2011 conversation attested to during the hearing, Wood was said to have told a prospective buyer that it would cost $1.5 million to fix the mall's roof and reportedly warned that the structure had to be fixed or the roof would cave in.

Wood was stripped of his professional engineering license in November 2011 after admitting to misconduct related to the mall.

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