Phase III of Concrete Roof Deck Moisture Research

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BACKGROUND

Moisture issues in low-slope roof systems installed over structural concrete roof decks have been a major concern for the roofing industry for over a decade. Prior to the turn of the 21st century, the attachment method for a low-slope roof to structural concrete would have been hot-mopped asphalt. This asphalt not only functioned as an adhesive for the roof system to the concrete roof deck, but the glaze mopping to these concrete decks also acted as a continuous vapor retarder. This had the effect of regulating moisture movement between the concrete and the compact roof assembly.

However, around the turn of the 21st century, the roofing industry began to move away from hot-mopping asphalt to alternative attachment methods. Specifically, low-rise foam adhesives began to replace hot-mopped asphalt as an attachment method of choice for all roof systems, including those over structural concrete roof decks. This change in products had its advantages, but the industry had inadvertently removed the vapor-retarding layer between the structural concrete roof deck and the roof system.

Slowly, problems began to emerge across the country, with roofs experiencing failures from high moisture levels. The typical failure mode was a loss of the membrane attachment in wind speeds well below design loads. Investigations conducted by numerous manufacturers, architects, engineers, and envelope consultants around North America would find elevated to saturated moisture levels in materials of the roof system. In general, many of these investigations concluded there must be an issue with bulk water leakage, air intrusion from the building, condensation, or even wet materials that had been installed as the cause of the observed moisture, with many missing the latent moisture in the concrete roof deck as the primary source of moisture.

Around 2010, the National Roofing Contractors Association (NRCA) began to recognize a pattern in the roof failure issues brought to their Technical Operations Committee. This was that a particular type of structural concrete, lightweight structural concrete (LWSC), was involved in many of the failure cases. The recognition of this pattern soon turned the attention to the latent moisture in normal-weight structural concrete (NWSC) as well as the LWSC.

For clarity, lightweight insulating concrete (LWIC) and the inherent moisture issues this roof deck brings to a roof system installed over LWIC have been well known and documented by the roofing industry. Therefore, any discussion herein about concrete roof decks is specific to structural concrete decks and not insulating concrete.

In 2011, Dupuis and Graham authored a paper on contemporary roofing issues.[1] This paper examined, among other issues, concrete moisture and concerns with latent moisture. This was followed shortly by technical bulletins from the Midwest Roofing Contractors Association[2] in 2011 and the NRCA[3] in 2013, warning of latent moisture in concrete and specifically the additional moisture contained within LWSC. Concurrently, Condren, Pinon, and Scheiner[4] published an article examining mix water involved in the production of concrete but concluded that more research was needed. Doelp and Moser[5] published a convention paper that examined the issue of concrete deck moisture but ultimately focused on moisture resistance of gypsum-based cover boards and high-density polyisocyanurate (HD ISO) based cover boards.

Possibly the best comprehensive sources on concrete moisture within slabs on grade and elevated slabs for floors were produced by Kanare[6] and Hedenblad.[7] This work was generally focused on concrete floors and the latent moisture content within. Specifically, Hedenblad's research directly led to the creation of the ASTM F2170[8] in-situ relative humidity probe test for concrete flooring.

Kanare's 2008 book[6] remains an authoritative and comprehensive treatment on moisture movement and flooring related moisture concerns. In a meeting with Kanare, years ago, he identified the key difference a concrete slab for roof decks faces that those he studied did not. That is that concrete slabs utilized for roof decks are exposed to the elements while they cure and before they are roofed over. Slabs utilized for flooring are generally protected from the elements and allowed to dry down before floor installation. In his book, Kanare[6] stated the following:

> *Rain that occurs after finishing is complete and the concrete has hardened for several hours generally does not damage the concrete surface. In fact, keeping the slab wet aids in curing, promotes cement hydration, and increases concrete strength. However, rain on a slab that has partly dried can create problems. The rate of drying for a slab that is rewetted (after it has begun to dry) is slower than its initial drying rate. This is because the concrete becomes more dense and less permeable as more cement hydrates. Water that migrates into a slab several months after placement will diffuse outward more slowly from the body of the concrete toward the surface where it can evaporate, compared to the original batch water. Rewetting can significantly lengthen the total drying time required.*

What Kanare's observation identified was what would become the true issue for concrete roof decks: external moisture sources.

Given the persistent questions on latent moisture levels in the concrete roof decks, several major roofing industry groups contributed funding to study the issue of latent concrete roof deck moisture beginning in 2015.

RESEARCH TO DATE

Phase I

In late 2015, what is now referred to as Phase I of the concrete research project began. With the issue of rewetting in mind, the Phase I work looked to quantify the effects of weather on the drying of concrete roof slabs. Additionally, the suitability of different test methods to assess the concrete moisture were examined. The test methods utilized were drilled in ASTM F2170 probes, the Tramex CMEXpert II Digital Concrete Moisture Meter, and gravimetric methods.

A large area behind SRI Consultants' (SRI's) laboratory in Middleton, WI, was converted to an external test site. In this area, eight 6 in. (152 mm) thick concrete slabs measuring 5 ft × 5 ft (1.5 m × 1.5 m) in size were cast. The experimental factors in this experiment were concrete type (LWSC versus NWSC), concrete finish (magnesium float versus hard steel trowel), and form type (steel form deck versus stripped form).

For the concrete used, a regional concrete supplier (Lycon Inc.) was contacted. SRI informed the supplier that these would be concrete roof decks and requested their most common NWSC and LWSC for this purpose. The supplier provided a 4,000 psi (28 MPa) mix for each concrete type.

SRI retained one of the larger regional general contractors (J.H. Findorff & Son Inc.). This contractor assisted with forming the slabs, placing reinforcing steel, placing the concrete, and finishing the concrete.

In addition to the slabs, 12 in. × 12 in. × 6 in. (305 mm × 305 mm × 152 mm) deep steel pans were cast with LWSC and NWSC. These pans were placed in racks on the simulated construction site and left exposed to the same weather as the slabs. These concrete samples allowed for gravimetric measurements over the course of the study.

For means of comparison, one slab of each of LWSC and NWSC was poured inside the laboratory, along with a full set of companion concrete pan samples that were cast and kept in the laboratory. The final component of the Phase I work at SRI was a full weather station that was installed to collect wind speed, wind direction, air temperature, air relative humidity, solar radiation, precipitation rate, and precipitation amount. This weather station collected data for the duration of the experiment.

In all, thousands of data points were collected and hundreds of ASTM F2170 probes were drilled into these slabs for readings.

The Phase I work also involved samples cast strictly for use in water vapor transmission testing (ASTM E96[9]) and hygrothermal characterization. One of the unknown items was the vapor transmission changes that happen to the concrete as it cures. As concrete goes through the chemical process of hydration, the pores, capillaries, and physical structure of the concrete change. **Figure 1** shows the results of the ASTM E96 testing. The results show that the hydration of portland cement does cause changes in the moisture transmission behavior. Additionally, one can easily observe that NWSC allows moisture to move approximately twice as fast as LWSC.

	Phase 1 - ASTM E96 calculated Perm·in.			
	Light Weight Structural Concrete		Normal Weight Concrete	
Age	Wet Cup	Dry Cup	Wet Cup	Dry Cup
28 Day	1.48	0.78	3.42	1.05
60 Day	1.45	0.47	2.03	1.13

Figure 1. *A table of results for ASTM E96 water vapor transmission testing for concrete samples from the Phase I research work.*

The final piece of work for the Phase I work was hygrothermal analysis of the wetting and drying of these slabs. Hygrothermal analysis was carried out with the contemporary release of the WUFI Pro hygrothermal simulation software. Those unfamiliar with the WUFI program and its capabilities can visit the manufacturer's website at www.wufi.de. It will suffice to describe the WUFI Pro package as a finite element program capable of simulating heat and moisture movement through roofs and walls. When combined with the data collected from the weather station, the impact of dew and condensate on the moisture content of the concrete slabs was apparent when comparing the collected data to what the program predicted. The exposure to the outdoor weather would allow the slabs to dry down but then rewet with precipitation and/or dew to where the slab moisture levels started or higher.

The result of the Phase I work provided three major conclusions. First, the issue of rewetting was the critical problem for roofing over new concrete roof decks. Effectively, the installer is forced to guess how much moisture lurks latent under the concrete surface based on rewetting versus drying time. Secondly, the instruments available were of little help. Electronic moisture meters were only capable of detecting very near surface moisture. They were perfect for determining whether the surface was dry but incapable of detecting elevated moisture mere fractions of an inch into the concrete slab, where a majority of the moisture is held. The third and final conclusion of Phase I was the value of the hygrothermal modeling in predicting moisture levels in the concrete slabs.

The conclusions of Phase I led to more funding for Phase II work.

Phase II

Phase II of the research work focused on three major efforts. The first effort was to validate the WUFI Pro modeling for roof systems over concrete roof decks. This specifically was to measure movement and quantity of moisture from concrete slabs into actual roof systems. This was done inside SRI's laboratory. Another experiment was constructed. The factors of LWSC versus NWSC, steel form deck versus stripped form slabs, and vapor retarder versus no vapor retarder were studied. Slabs were cast inside the laboratory from the same supplier and mixes from Phase I. Half were LWSC; the other half were NWSC. Half utilized steel form deck; the other half had strippable forms. These slabs were allowed to cure and dry for 28 days in the laboratory. In addition, two slabs, one NWSC and one LWSC, were cast over load cells to quantify the moisture loss by weight. In all, 10 slabs were cast and utilized for the phase of work.

On exactly day 28, they were roofed with a multilayer polyisocyanurate insulation system using paper facers (ASTM C1289 Type II, Class 1) and a directly adhered 60-mil (1.5 mm) thermoplastic olefin (TPO) system. Half of the concrete decks received a torch-applied styrene-butadiene-styrene polymer-modified bitumen base sheet as a vapor retarder. During assembly of these roofs, numerous miniature high-accuracy temperature and humidity sensors were installed and linked to a data-logging PC.

Concurrently, large samples of the concrete used were shipped to a Canadian laboratory for more precise hygrothermal characterization. These slabs, now roofed and instrumented, were left for 1 year to allow moisture movement and measurement. **Figure 2** shows these slabs in the laboratory.

The hygrothermal material data, returned from Canada, were entered into the WUFI program. The WUFI program then very accurately predicted, almost to the hour, the moisture movement from the concrete to the underside of the TPO membrane and underlying polyisocyanurate facer. **Figure 3** shows one of the roof systems' collected data versus the predicted WUFI data. The model was considered validated for this application and a viable tool to predict concrete moisture movement in a roof system.

Figure 2. *Photo of instrumented roofs over concrete decks at SRI's Middleton, WI, laboratory. Slabs were heated from below to 90°F (32°C) to provide a positive vapor gradient across the roof system.*

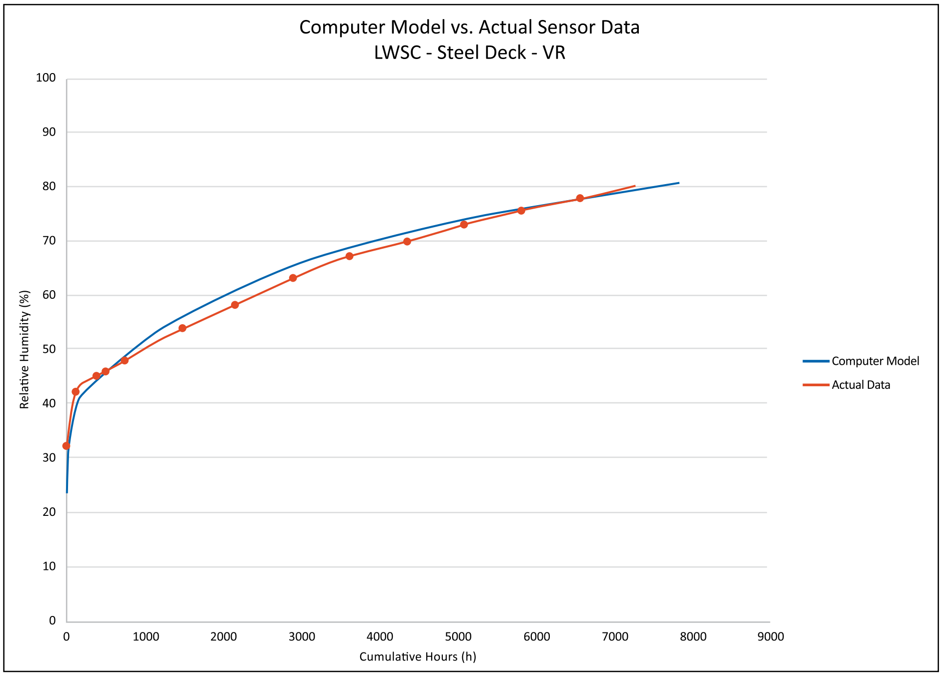


Figure 3. *A graph of the measured humidity at a specific point in the roof system versus the predicted value from the WUFI simulation.*

The final component of the Phase II work was to utilize the WUFI Pro program, now validated for this specific roofing condition, to conduct a carefully planned series of simulations of slabs and then roof systems. The exact simulation conditions, locations, and material data fed into WUFI are contained in the final report issued to the NRCA and the Alliance for Roofing Progress.[10] A copy of this report can be obtained from the NRCA.

Over 1,000 WUFI simulations were conducted as part of the Phase II work. A representative major city from each of the American Society for Heating and Refrigeration Engineers (ASHRAE) climate zones (1 to 7) was chosen as representative for purposes of studying the moisture behavior of roofs installed over concrete roof decks in these cities. For this work, a TPO roof with two layers of polyisocyanurate employing a paper facer was used as the most common roof utilized across the US.

The results of these simulations are detailed in the report.[10] However, the conclusions reached were that a strong vapor retarder of 0.01 perms is needed to protect the roof system from transient concrete moisture in every ASHRAE climate zone except Zone 1 (Miami, FL). This was due in no small part to the issue of rewetting. This conclusion has generally guided the roofing industry since the report's publication in 2020.

PHASE III RESEARCH

Purpose of Phase III

With the publication of the Phase I and II results in 2020, there was a minimum design recommendation, in this report, for low-slope roofs over new concrete decks. That was to assume the concrete deck contained high moisture content from rewetting and provide a strong vapor retarder over the concrete to control latent moisture migration into the new roof system.

However, an obvious question arose surrounding reroofing over concrete decks: Can a new roof system be safely installed over an existing structural concrete roof deck during a reroof? The only guidance that it was possible to give was to utilize common sense. This approach was to assess the moisture condition of the roof being torn off. If it was dry, one could presume the structural concrete deck was suitable for a reroof lacking a vapor retarder. If the roof being torn off was moisture laden (wet), one could presume the concrete deck contained latent moisture and utilize a vapor retarder in the reroof.

Even mixed conditions could be addressed within a reroof not utilizing a vapor retarder. This means that in areas of dry existing roof being torn off, do not use a vapor retarder. If during the reroof the crew encountered an area of wet insulation, install a vapor retarder in this area and extend it beyond the wet perimeter by some arbitrary and conservative amount, such as 4 ft (1.2 m) beyond the perimeter of the wet roof system.

However, the issue remained that there was no accepted method for determining the moisture content of the concrete deck. The designer, manufacturer, or roofing contractor was left with a binary choice; the deck was either considered wet or dry, with no potential middle ground.

INTRODUCTION OF INSTANT CONCRETE MOISTURE ASSESSMENT AT DEPTH

In the recent past, one manufacturer has released an electrical induction-based measurement of concrete moisture at depth. This test is conducted in a similar manner to the ASTM F2170 test, where a ¾ in. (19 mm) hole is drilled into the concrete slab to a specified depth.

With the new system, an emitting probe is inserted into the drilled hole, and an electric field is created between the probe, at depth, and the meter placed on the surface of the slab. Effectively, this creates a transmitter-receiver relationship. The meter reading is instantaneous and reads moisture content as a percentage in the concrete.

While the manufacturer does have published instructions for conducting readings, no consensus standard procedure yet exists, such as an ASTM test standard. However, this is a large leap for the roofing industry, where we can now assess moisture content at depth, nearly instantaneously. The only limitation SRI learned from Phases I and II research was that real-time data logging of F2170 probes inserted into drilled holes showed that the moisture readings were affected by the drilling process. This was hypothesized to be related to the heat of drilling the hole in the concrete. However, temperature and humidity readings in the hole normalized approximately 1 hour after drilling. Therefore, this may be part of a future standard procedure.

EXPERIMENTAL PLAN

With a new method to assess structural concrete roof slab moisture rapidly in the field, an experimental plan was drafted to examine the potential of geographical location for a roof versus how much moisture was allowable for roofing over a concrete deck without a vapor retarder.

In addition to routine questions on the moisture content of the concrete deck, SRI has been routinely questioned on the benefit of the use of a cover board, specifically gypsum-based cover boards and HD ISO cover boards.

Given the availability of the WUFI program, validated with roof systems over moisture-laden concrete, SRI formulated an experimental plan to conduct experimental hygrothermal simulations.

Typical forensic failure investigations or external inquiries from roofing contractors almost always involve paper-faced polyisocyanurate insulation. The most common failure mode for moisture-laden roof systems over structural concrete decks is the loss of attachment during wind uplift due to cohesive failure within the paper insulation facer or occasionally the dissolution of gypsum-based cover board's core.

The simulations were conducted for nine different ASHRAE climate zones representing major climates in North America. These climates were the following:

- 1A Miami, FL
- 2A Houston, TX
- 3A Atlanta, GA
- 3B Las Vegas, NV
- 4A Nashville, TN
- 4C Seattle, WA
- 5A Chicago, IL
- 6A Minneapolis, MN
- 7A Calgary, AB

In Phases I and II of the research, the membrane focused on was white TPO, as it represented the most common roof system installed in the US.[11] This aside, many have wondered whether using a membrane with a lower solar reflectivity, operating at a higher daytime temperature, would improve the resilience of roofs over concrete roof decks. Therefore, both 60-mil (1.5 mm) black ethylene propylene diene monomer (EPDM) and white 60-mil (1.5 mm) TPO membranes were simulated.

While the structural concrete roof deck can vary in thickness from building to building, the most common thickness observed has been 6 in. (15.24 cm) depth over a metal form deck. Therefore, simulations utilized a 6 in. thick NWSC deck over a 20 ga metal deck.

Both gypsum-based cover boards and HD ISO cover boards were part of the simulations, in addition to these membranes directly adhered to the polyisocyanurate insulation. Therefore, six different roof configurations were simulated:

- 60-mil (1.5 mm) black EPDM/2 in. × 2 in. (51 mm × 51 mm) paper-faced polyisocyanurate/6 in. (152 mm) NWSC deck
- 60-mil (1.5 mm) black EPDM/½ in. (13 mm) gypsum cover board/2 in. × 2 in. (51 mm × 51 mm) paper-faced polyisocyanurate/6 in. (152 mm) NWSC deck
- 60-mil (1.5 mm) black EPDM/½ in. (13 mm) HD ISO cover board/2 in. × 2 in. (51 mm × 51 mm) paper-faced polyisocyanurate/6 in. (152 mm) NWSC deck
- 60-mil white TPO/2 in. × 2 in. (51 mm × 51 mm) paper-faced polyisocyanurate/6 in. (152 mm) NWSC deck
- 60-mil white TPO/½ in. (13 mm) gypsum cover board/2 in. × 2 in. (51 mm × 51 mm) paper-faced polyisocyanurate/6 in. (152 mm) NWSC deck
- 60-mil white TPO/½ in. (13 mm) HD ISO cover board/2 in. × 2 in. (51 mm × 51 mm) paper-faced polyisocyanurate/6 in. (152 mm) NWSC deck

Figure 4 shows a cross-section depiction of the roofs simulated, with and without a cover board.

These roof systems were simulated in their respective cities using the "cold year" file for 5 years. The critical reflectivity values were selected based on the author's experience in field reflectivity measurement and published research.[12] The interior environment was held constant with a sinusoidal temperature and

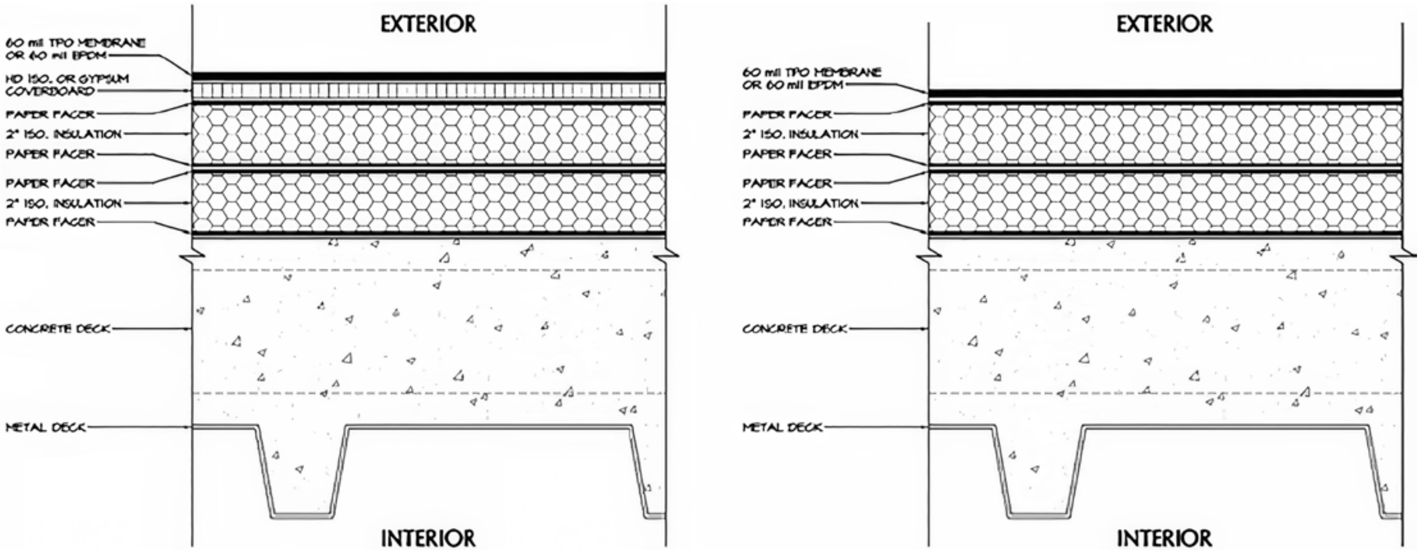


Figure 4. *A cross-section depiction of the roofs simulated in various ASHRAE zones and at varying moisture content for the normal-weight structural concrete deck.*

humidity (68°F to 72°F [20°C to 22°C]; 30% to 50% relative humidity [RH]).

The major variable studies with each roof, in each city, were the varying amounts of concrete deck moisture simulated. The values selected were taken from the laboratory results from the Phase II work, where the concrete was hygrothermally characterized. The laboratory produced moisture content levels for equilibrium moisture contents (EMCs) for five practical points to simulate a starting moisture content of the NWSC:

- 1.08 lb/ft^3 (17.3 kg/m^3)/0.50 RH/0.8% moisture content
- 1.89 lb/ft^3 (30.2 kg/m^3)/0.80 RH/1.3% moisture content
- 2.44 lb/ft^3 (39.1 kg/m^3)/0.90 RH/1.7% moisture content
- 3.43 lb/ft^3 (54.9 kg/m^3)/0.95 RH/2.4% moisture content
- 7.57 lb/ft^3 (121.3 kg/m^3)/1.00 RH/5.4% moisture content

This experimental plan produced 270 simulations with an aggregate of almost 12 million simulated hours.

RESULTS

The numerical results were evaluated against manufacturers' advertised limits of moisture content acceptability for gypsum cover boards, research by others,[5] and the author's research on polyisocyanurate facers.[13]

The simulated roof was considered to "pass" if, at no point in the 5 years simulated, did any component reach an unacceptable moisture content.

A roof system was deemed a "marginal" result if, at any point in the 5 years, the moisture content exceeded the acceptable level but returned to an acceptable moisture level during the 5 years. This condition typically was observed as one, or more, paper polyisocyanurate facers in the cross section exceeding 6 lb/ft^3 (96.1 kg/m^3) moisture content. As a hypothetical, a facer may exceed this amount briefly during the winter condition of the first year but dry down quickly and never exceed this amount in consecutive winters. Paper facers are documented to regain their strength upon drying. Therefore, these are deemed "marginal" cases.

A "fail" is recorded if any component greatly exceeded the acceptable moisture content for any cover board or facer in consecutive seasonal cycles, continually gained moisture, or remained saturated.

Of note, biological growth potential was not assessed. Experienced practitioners and roofing professionals are well versed in the biological growth potential for organic (paper) facers used on current polyisocyanurate insulation when they are left in the roof with elevated moisture content. The WUFI Pro package contains a post-processor program (WUFI-Bio) that can analyze the risk of biological growth on a construction material. As this is a separate issue and not related to the typical primary complaint of wind uplift failure involved with latent concrete roof deck failures, the subject is set aside for possible future work.

Figures 5–10 are the results of the simulations, tabulated and color coded for quick visual assessment.

OBSERVATIONS

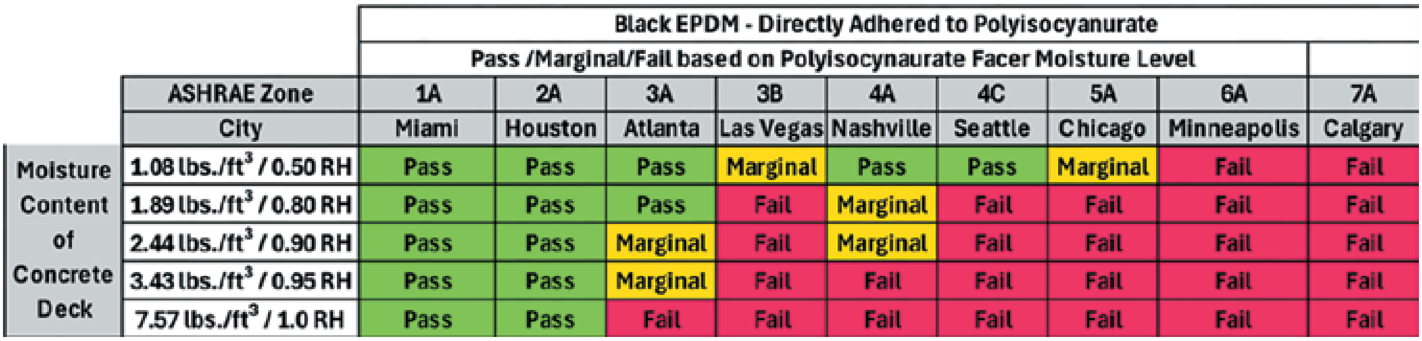
There are multiple observations that can be drawn from the simulation results:

1. The hygrothermal forces on a roof system installed over what any reasonable person would consider dry concrete (0.50 RH/EMC) can potentially lead to unacceptable roof performance, even in desert climates.
2. Gypsum-based cover boards appear to provide some hygric buffer capacity and can assist the roof in certain design scenarios. However, they do not solve the problem of latent moisture.
3. Many of the "marginal" and "fail" roof simulations can be moved into a "pass" scenario with moisture-insensitive materials. This specifically means switching to coated glass facers for the polyisocyanurate (ASTM C1289 Type II, Class 2), as a majority of the failures were in the paper facers. This also removes the only organic component in the roof system, generally eliminating biological growth concerns.

CONCLUSIONS

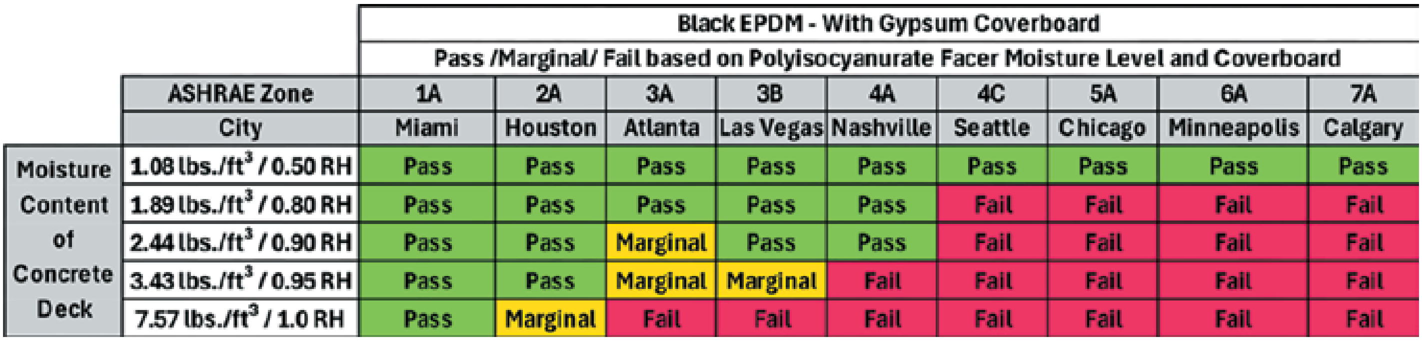
Based on the research conducted (Phases I, II, and III) and respectable amounts of field forensics and investigations, the following conclusions are offered:

1. Roofs installed over NWSC decks in ASHRAE climate zone 1 appear to function independently of the moisture content in the concrete deck.
2. Roofs installed over NWSC decks in ASHRAE climate zones 2, 3, and 4 are very sensitive to the moisture content of the concrete deck at the time of installation. Moisture content testing of the concrete and a roof design accounting for the moisture levels are recommended. If the roof designer cannot conservatively assure moisture performance



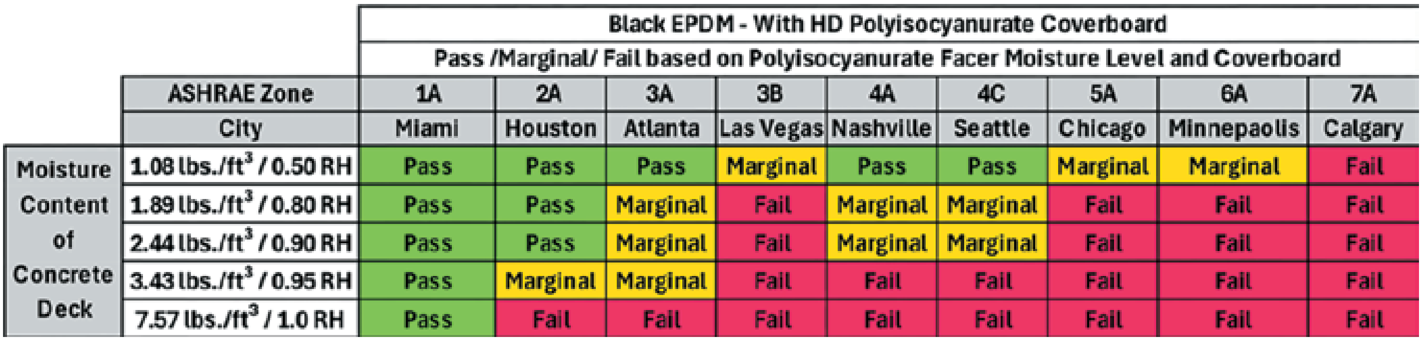
		Black EPDM - Directly Adhered to Polyisocyanurate								
		Pass /Marginal/Fail based on Polyisocynaurate Facer Moisture Level								
	ASHRAE Zone	1A	2A	3A	3B	4A	4C	5A	6A	7A
	City	Miami	Houston	Atlanta	Las Vegas	Nashville	Seattle	Chicago	Minneapolis	Calgary
Moisture Content of Concrete Deck	1.08 lbs./ft^3 / 0.50 RH	Pass	Pass	Pass	Marginal	Pass	Pass	Marginal	Fail	Fail
	1.89 lbs./ft^3 / 0.80 RH	Pass	Pass	Pass	Fail	Marginal	Fail	Fail	Fail	Fail
	2.44 lbs./ft^3 / 0.90 RH	Pass	Pass	Marginal	Fail	Marginal	Fail	Fail	Fail	Fail
	3.43 lbs./ft^3 / 0.95 RH	Pass	Pass	Marginal	Fail	Fail	Fail	Fail	Fail	Fail
	7.57 lbs./ft^3 / 1.0 RH	Pass	Pass	Fail	Fail	Fail	Fail	Fail	Fail	Fail

Figure 5. *Results of black ethylene propylene diene monomer (EPDM) directly adhered to polyisocyanurate.*



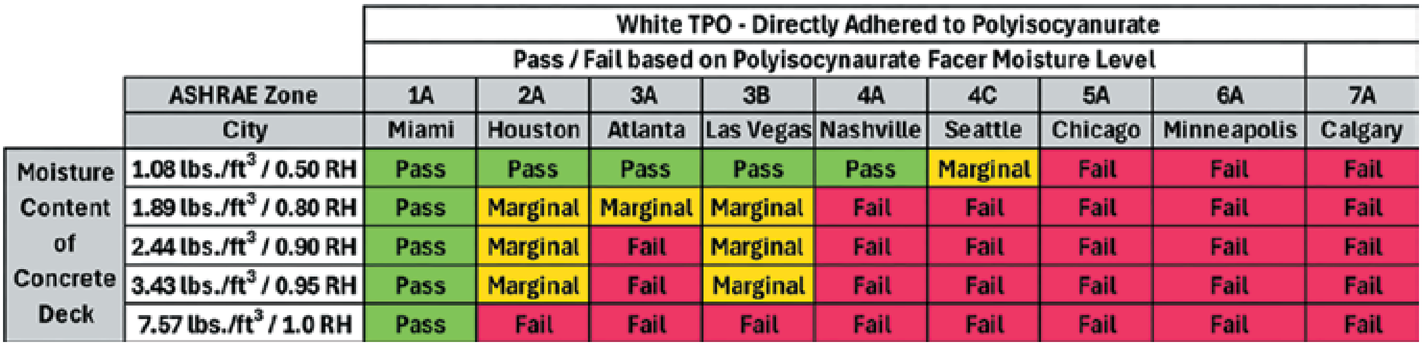
		Black EPDM - With Gypsum Coverboard								
		Pass /Marginal/ Fail based on Polyisocyanurate Facer Moisture Level and Coverboard								
	ASHRAE Zone	1A	2A	3A	3B	4A	4C	5A	6A	7A
	City	Miami	Houston	Atlanta	Las Vegas	Nashville	Seattle	Chicago	Minneapolis	Calgary
Moisture Content of Concrete Deck	1.08 lbs./ft^3 / 0.50 RH	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass
	1.89 lbs./ft^3 / 0.80 RH	Pass	Pass	Pass	Pass	Pass	Fail	Fail	Fail	Fail
	2.44 lbs./ft^3 / 0.90 RH	Pass	Pass	Marginal	Pass	Pass	Fail	Fail	Fail	Fail
	3.43 lbs./ft^3 / 0.95 RH	Pass	Pass	Marginal	Marginal	Fail	Fail	Fail	Fail	Fail
	7.57 lbs./ft^3 / 1.0 RH	Pass	Marginal	Fail	Fail	Fail	Fail	Fail	Fail	Fail

Figure 6. *Results of black ethylene propylene diene monomer (EPDM) with a gypsum cover board.*



		Black EPDM - With HD Polyisocyanurate Coverboard								
		Pass /Marginal/ Fail based on Polyisocyanurate Facer Moisture Level and Coverboard								
	ASHRAE Zone	1A	2A	3A	3B	4A	4C	5A	6A	7A
	City	Miami	Houston	Atlanta	Las Vegas	Nashville	Seattle	Chicago	Minneapolis	Calgary
Moisture Content of Concrete Deck	1.08 lbs./ft^3 / 0.50 RH	Pass	Pass	Pass	Marginal	Pass	Pass	Marginal	Marginal	Fail
	1.89 lbs./ft^3 / 0.80 RH	Pass	Pass	Marginal	Fail	Marginal	Marginal	Fail	Fail	Fail
	2.44 lbs./ft^3 / 0.90 RH	Pass	Pass	Marginal	Fail	Marginal	Marginal	Fail	Fail	Fail
	3.43 lbs./ft^3 / 0.95 RH	Pass	Marginal	Marginal	Fail	Fail	Fail	Fail	Fail	Fail
	7.57 lbs./ft^3 / 1.0 RH	Pass	Fail	Fail	Fail	Fail	Fail	Fail	Fail	Fail

Figure 7. *Results of black ethylene propylene diene monomer (EPDM) with a high-density (HD) polyisocyanurate cover board.*

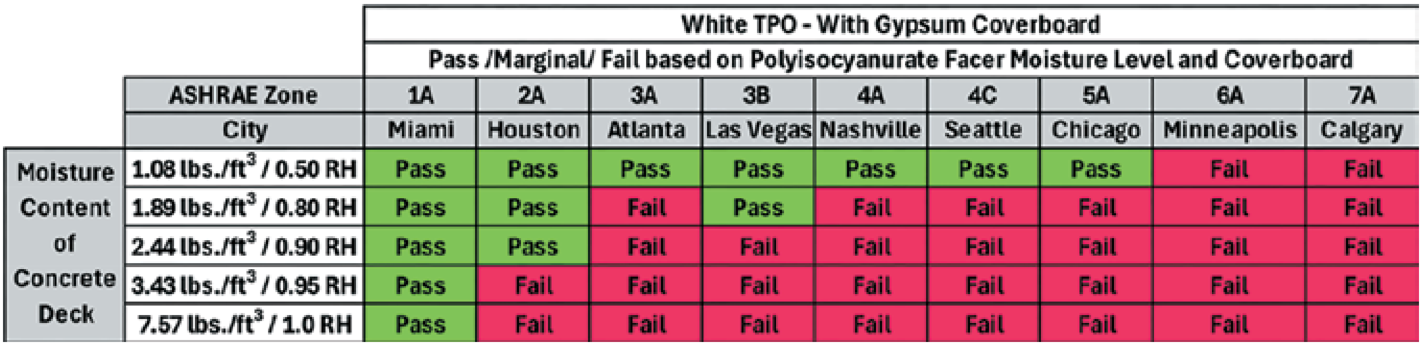


		White TPO - Directly Adhered to Polyisocyanurate								
		Pass / Fail based on Polyisocynaurate Facer Moisture Level								
	ASHRAE Zone	1A	2A	3A	3B	4A	4C	5A	6A	7A
	City	Miami	Houston	Atlanta	Las Vegas	Nashville	Seattle	Chicago	Minneapolis	Calgary
Moisture Content of Concrete Deck	1.08 lbs./ft^3 / 0.50 RH	Pass	Pass	Pass	Pass	Pass	Marginal	Fail	Fail	Fail
	1.89 lbs./ft^3 / 0.80 RH	Pass	Marginal	Marginal	Marginal	Fail	Fail	Fail	Fail	Fail
	2.44 lbs./ft^3 / 0.90 RH	Pass	Marginal	Fail	Marginal	Fail	Fail	Fail	Fail	Fail
	3.43 lbs./ft^3 / 0.95 RH	Pass	Marginal	Fail	Marginal	Fail	Fail	Fail	Fail	Fail
	7.57 lbs./ft^3 / 1.0 RH	Pass	Fail	Fail	Fail	Fail	Fail	Fail	Fail	Fail

Figure 8. *Results of white thermoplastic olefin (TPO) directly adhered to polyisocyanurate.*

based on the concrete moisture levels, such as through hygrothermal simulation, the default design should still include a moisture mitigation aspect, such as a vapor retarder.

3. Roofs installed over NWSC decks in ASHRAE climate zones 5 and higher should always include a moisture mitigation technique, such as a vapor retarder, as the default. Even roofs at the lowest simulated moisture levels produced marginal results, at best.
4. The creation of a consensus instantaneous concrete roof deck moisture level test, such as a standard test method at ASTM, is needed.

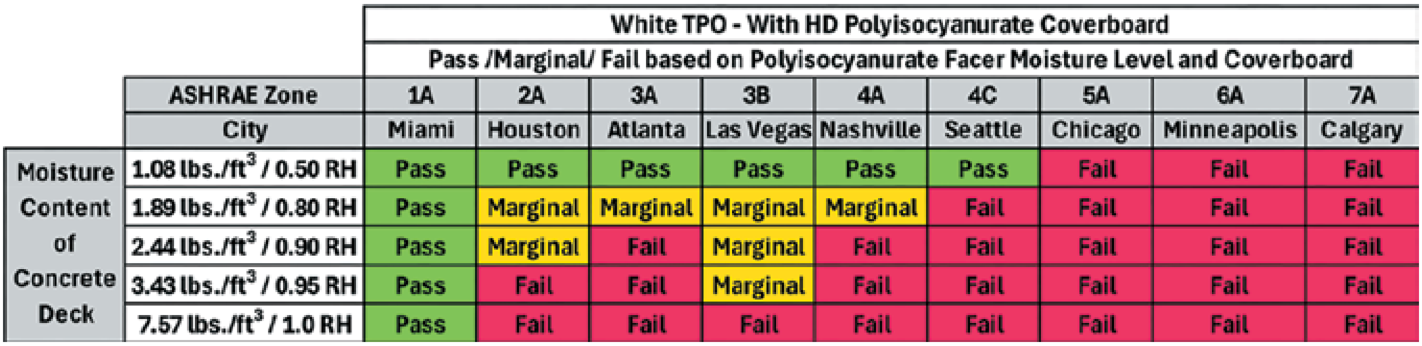


White TPO - With Gypsum Coverboard

Pass /Marginal/ Fail based on Polyisocyanurate Facer Moisture Level and Coverboard

	ASHRAE Zone	1A	2A	3A	3B	4A	4C	5A	6A	7A
	City	Miami	Houston	Atlanta	Las Vegas	Nashville	Seattle	Chicago	Minneapolis	Calgary
Moisture Content of Concrete Deck	1.08 lbs./ft^3 / 0.50 RH	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Fail	Fail
	1.89 lbs./ft^3 / 0.80 RH	Pass	Pass	Fail	Pass	Fail	Fail	Fail	Fail	Fail
	2.44 lbs./ft^3 / 0.90 RH	Pass	Pass	Fail	Fail	Fail	Fail	Fail	Fail	Fail
	3.43 lbs./ft^3 / 0.95 RH	Pass	Fail	Fail	Fail	Fail	Fail	Fail	Fail	Fail
	7.57 lbs./ft^3 / 1.0 RH	Pass	Fail	Fail	Fail	Fail	Fail	Fail	Fail	Fail

Figure 9. *Results of white thermoplastic olefin (TPO) with gypsum cover board.*



White TPO - With HD Polyisocyanurate Coverboard

Pass /Marginal/ Fail based on Polyisocyanurate Facer Moisture Level and Coverboard

	ASHRAE Zone	1A	2A	3A	3B	4A	4C	5A	6A	7A
	City	Miami	Houston	Atlanta	Las Vegas	Nashville	Seattle	Chicago	Minneapolis	Calgary
Moisture Content of Concrete Deck	1.08 lbs./ft^3 / 0.50 RH	Pass	Pass	Pass	Pass	Pass	Pass	Fail	Fail	Fail
	1.89 lbs./ft^3 / 0.80 RH	Pass	Marginal	Marginal	Marginal	Marginal	Fail	Fail	Fail	Fail
	2.44 lbs./ft^3 / 0.90 RH	Pass	Marginal	Fail	Marginal	Fail	Fail	Fail	Fail	Fail
	3.43 lbs./ft^3 / 0.95 RH	Pass	Fail	Fail	Marginal	Fail	Fail	Fail	Fail	Fail
	7.57 lbs./ft^3 / 1.0 RH	Pass	Fail	Fail	Fail	Fail	Fail	Fail	Fail	Fail

Figure 10. *Results of white thermoplastic olefin (TPO) with high-density (HD) polyisocyanurate cover board.*

5. A joint industry position between manufacturers, designers, and installers of roof systems requiring coated glass facers for the polyisocyanurate (ASTM C1289 Type II, Class 2) should be made. This alone would prevent many moisture-based roof system failures over concrete roof decks.

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