



Moisture Analysis in Unconditioned Concrete

By Kip Gatto, PE, SE; Grace Wong, AIA, LEED AP

Photo Courtesy Lexis Coatings.

INTRODUCTION

Moisture-sensitive materials such as adhesives and coatings (simplified as “coatings” for this article) are routinely applied to concrete surfaces in exterior plazas, roof structures, concourses, retention structures, parking garages, etc., for various purposes, including waterproofing and protection. The service environments for the coatings are often unconditioned—that is, in situations where the temperature and moisture conditions around the concrete element are not regulated. The success of these moisture-sensitive coating applications is often crucial for the performance of building envelope systems and for the protection of structural elements, and is dependent on the vapor drive behavior through the coated concrete assembly.

The negative effects of excessive moisture in concrete to the performance of adhesively applied surfacing materials are

well established and understood by the industry. Excessive moisture in concrete, leading to significant vapor drive, is one of the common causes of poor performance in adhesively applied materials. Vapor drive is commonly quantified in concrete by the concrete surface moisture vapor emission rate (MVER).

Currently, the vast majority of industry guidance regarding MVER is limited to concrete in interior, conditioned environments. Test protocols for measuring the moisture levels in concrete, and thresholds for acceptable MVERs and in-situ relative humidity (RH), are well established for regulated interior environments. However, there is no guidance on what is acceptable for a concrete element during construction prior to the HVAC system being commissioned. Conditioning the environment to 70°F (21°C) for the sole purpose of verifying moisture conditions in the concrete is not practical

in most cases.

In exterior applications that will never be conditioned, industry guidance is limited to the subjective plastic sheet method, which essentially consists of placing polyethylene against the concrete surface to assess whether moisture condenses. Some manufacturers provide RH as a guideline as well, but RH is a poor measure of conditioning in a variable temperature environment. The industry is in need of something better—at least for sensitive situations where coating failures can have inordinate consequences. This article studies options for taking the industry to the next level in this regard.

This study proposes a method of determining the threshold and acceptance criteria for application of moisture-sensitive coatings to concrete in unconditioned environments based on evaluating the maximum expected stresses on the coating-concrete

bond for arbitrary environmental conditions. As an intermediate step toward the state of the art, we also propose to use this framework to correlate current industry acceptance criteria for conditioned spaces with unconditioned environments.

ANALYSIS

Net vapor pressure is the difference in vapor pressure on the two surfaces of a coating (i.e., the surface that is adhered to concrete and the surface exposed to soil, liquid, air, etc.). For our analysis models, net vapor pressure (the difference in vapor pressure on each side of the coating) was used to evaluate the demand on the coating-concrete bond during service, presuming this is a good indicator of expected coating performance. Although this is different from the MVER and RH measurements used in the industry, it is presumed to be more useful in the context of this study.

Hygrothermal Model

Variables that affect vapor drive include soil or exterior climate, coating permeance, and the presence or absence of a vapor barrier. In order to understand the effects of these variables, studies were performed by building hygrothermal analysis models using WUFI software. The WUFI models were also used for sensitivity studies to understand the relative performance of coatings in industry-accepted conditions and also in unconditioned environments.

The WUFI models were calibrated using field data collected from temperature and RH probes installed in concrete elements in existing buildings. Three sets of probe data were used: one from a floor slab, one from a wall, and one from a roof deck. Three WUFI models were developed to reflect the respective constructions and environmental conditions at these locations (Figures 1 through 3). The calibrated WUFI models were then used in the subsequent parametric studies.

One of the most important findings from the WUFI validation models is that daily or even monthly climate fluctuations on one side of the concrete element do not significantly affect the condition of the concrete. This allows for simplification of hygrothermal models and decoupling the coating performance from seasonal climate trends. For our subsequent studies, simplified analysis models were used where the temperature and RH on each side of the coated concrete assembly are constant.

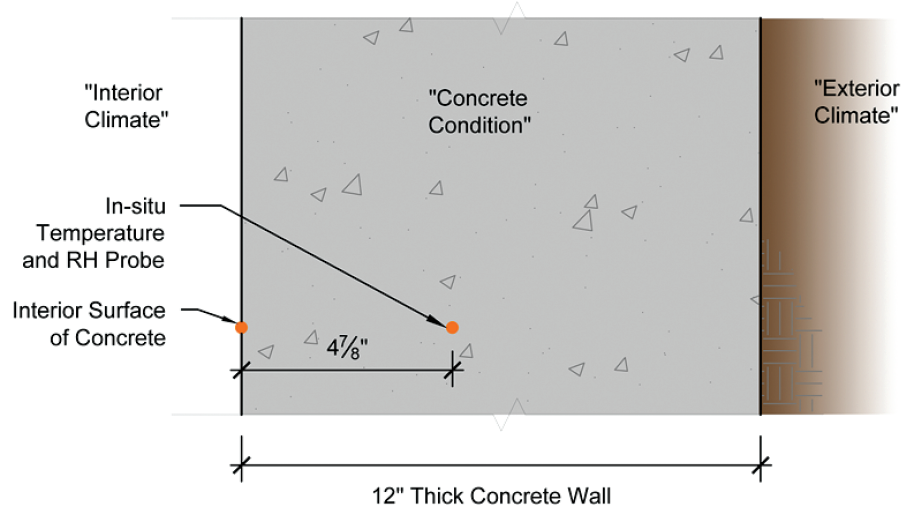


Figure 1 – WUFI Model 1: Below-grade concrete slab on ground.

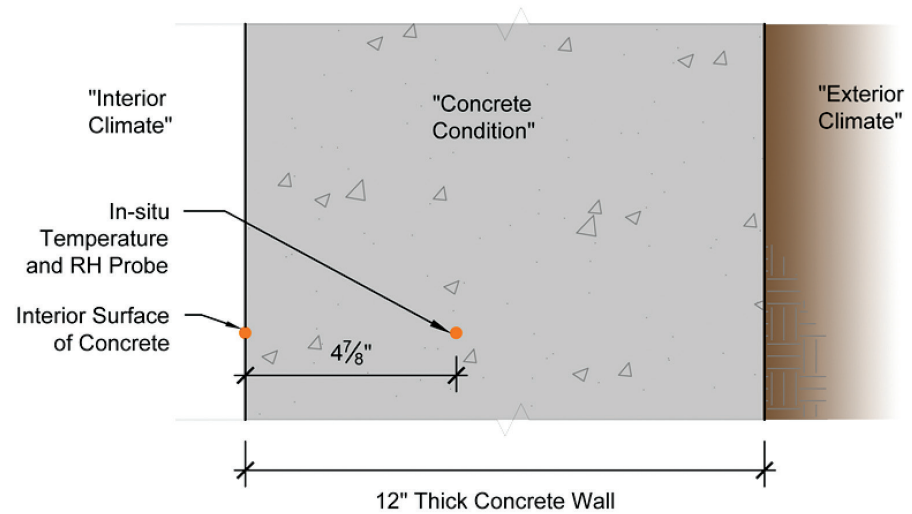


Figure 2 – WUFI Model 2: Below-grade wall.

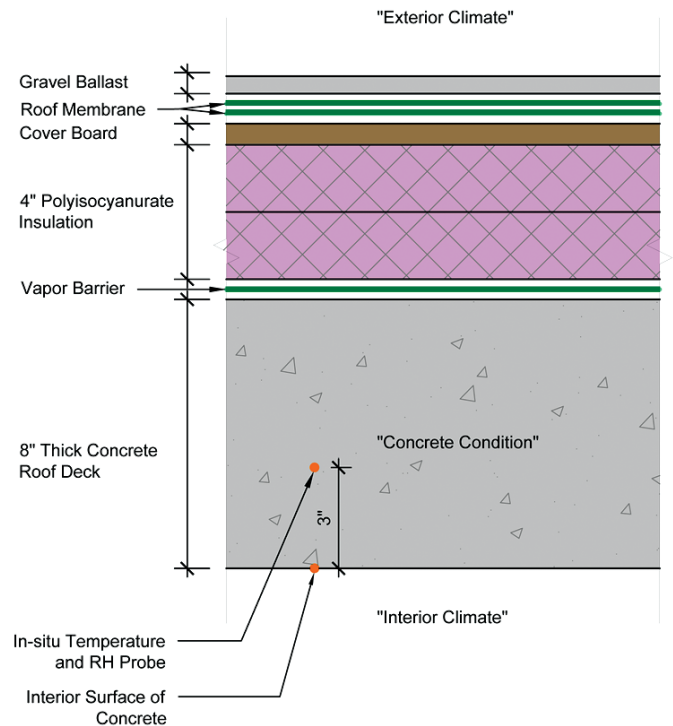


Figure 3 – WUFI Model 3: Built-up roof on concrete deck.

Effects of Coating and Coating Permeance

Theoretically, MVER is a function of the net vapor pressure across the coating and the permeance of the coating. For example, for a higher permeance at the same net vapor pressure, the predicted MVER will also be higher. The same MVER can also be obtained with a high-permeance coating at a low net vapor pressure as with a low-permeance coating at a high net vapor pressure. Four models were created to

investigate how coating permeance affects the net pressure experienced by the coating.

The results (*Figure 4*) show that the higher the permeance of the coating, the lower the net vapor pressure. For coatings at and above 1 perm, the net vapor pressure appears to generally decrease over time and reaches stabilized conditions within the first year. Higher-permeance coatings also tend to approach stabilized conditions faster. The low-permeance (0.1 perm) coating appears to be allowing pressure buildup behind the

coating. This is likely due to the continued supply of moisture to the concrete from the exterior, which is unable to dissipate quickly enough through a very low-perm coating.

Effects of Initial Temperature and RH

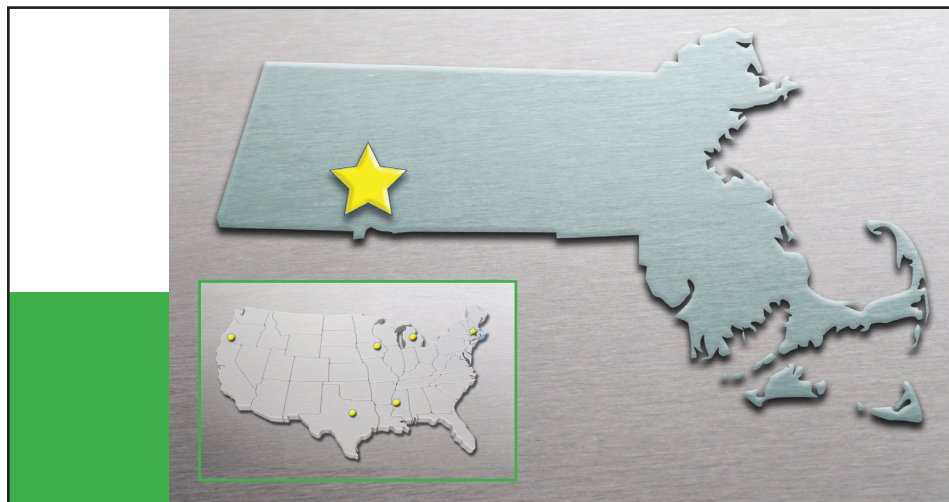
The use of the differential in temperature (DT) and differential in RH (DRH) between the interior and exterior environments was explored to characterize a group of similar assemblies. However, it was found that the net vapor pressure across a coating can be significantly different in varying environmental temperatures and RH conditions, even if DT and DRH are identical (*Figure 5*). This phenomenon is likely attributable to the nonlinear dependency of hygrothermal properties on temperature and RH for the materials modeled. The thermal conductivity of concrete increases nonlinearly with increased moisture content, and it also tends to take up moisture slower as its moisture content increases. That is to say, hot-wet slabs respond differently to changing conditions than cold-dry slabs. Despite the limitations, DT and DRH are useful for organizing findings in a tabular format for this limited-scope research.

Determining Acceptable Conditions for Coating Application

A flowchart was created to outline the possible conditions that may be encountered at a project site and corresponding possible courses of action (*Figure 6*). This flowchart is intended to be used in conjunction with the design guide tables, an example of which was developed in this study as *Tables A and B*, to aid in decision-making during the coating application process. In practice, a suite of these tables is envisioned to be developed for various concrete assemblies (roof, wall, slab, etc.), and for coatings with various hygrothermal properties. There could also be sets of tables developed for groups of temperature and RH conditions to account for the temperature and moisture dependency of materials. To provide a roadmap for this future research, a set of such tables was developed as part of this study to demonstrate their value.

Concrete Slab on Ground

A series of WUFI simulations was performed using the slab-on-ground model with a 4-in.-thick slab, no vapor barriers between the soil and concrete, and an applied 0.1-perm coating. *Table A* summarizes



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the results from the analyses. As expected, the net vapor pressure across the coating increases with increasing DT and DRH. Because of the time dependence of the net vapor pressure, three values were extracted from each model: one hour, 24 hours, and one year. These three timeframes are also useful for comparison with coatings undergoing different phases of curing. Many coatings are much more sensitive to vapor pressure during an early age when they are curing. A one-day-old coating application is typically more sensitive to vapor pressure than a one-year old coating. Knowing what the vapor pressure demand is at each of these time intervals is useful in assessing expected coating performance.

Table A allows for an example of how tables can be used to assess the expected performance of a coating. For example, if a coating manufacturer has deemed that it is acceptable to apply a coating when the concrete is conditioned to 70°F and 80% RH, with interior environment conditioned to be at 70°F and 60% RH, one can look up the entry in Table A that corresponds to DT = 0°F and DRH = +20%. There are three values in that entry corresponding to the one-hour, 24-hour, and one-year time intervals: 0.096

psi, 0.073 psi, and 0.027 psi, respectively. These vapor pressures are produced from the coating manufacturer-specified concrete and environmental conditioning, so it is presumed these pressures are acceptable to the manufacturer.

If, in reality, the coating is going to be applied during construction prior to the building enclosure, when the

outdoor conditions tend to be 90°F and 40% RH, one would compare the acceptable net vapor pressure values inferred from the manufacturer-approved condition, with the value in the entry that corresponds to DT = -20°F and DRH = +40%: 0.028 psi, 0.044 psi, and 0.014 psi, respectively. Given that these vapor pressures are lower than the values inferred from the manufacturer, it

Net Vapor Pressure Across Coating

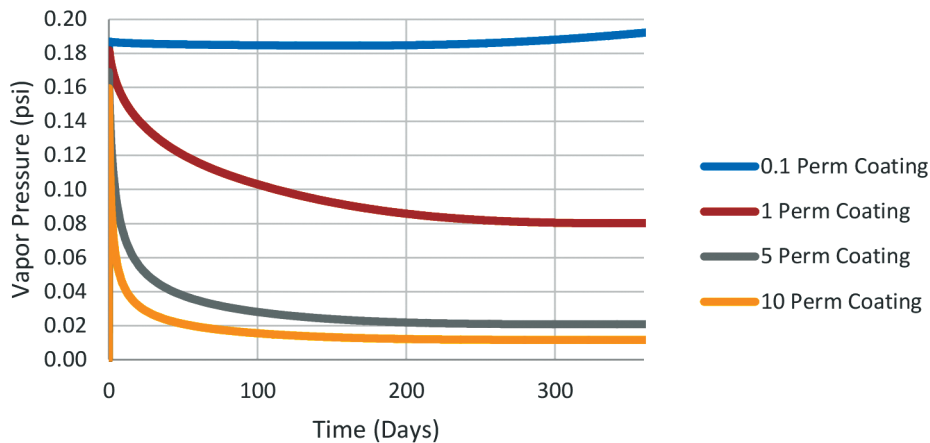


Figure 4 – Change in net vapor pressure across the coating over time for a concrete slab on grade with no under-slab vapor barrier. Note net vapor pressure buildup over time in the case of a 0.1 perm coating.



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Difference in Vapor Pressure Across Coating

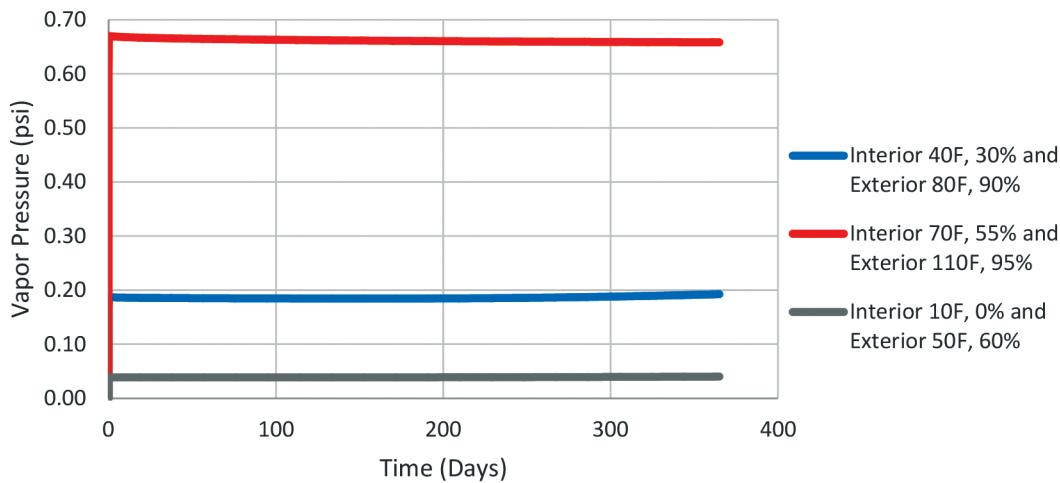


Figure 5 – Change in net vapor pressure across the coating over time for concrete in different environmental service conditions.

is reasonable to expect the coating will perform satisfactorily in service.

Clearly this is a leap that will require manufacturer approval and further refinement. However, the hope is that manufacturers will ultimately incorporate this broader criterion into their application procedures to better assist the industry in confident application of their materials.

Concrete Roof Deck

Similarly, analyses were performed on five representative sets of environmental conditions applied to the validated concrete roof deck model, with insulation and built-up roofing above the concrete deck. Half of the model was run through the summer (average $T = 80^{\circ}\text{F}$, $\text{RH} = 75\%$), and the other half was run through the winter (average $T = 50^{\circ}\text{F}$, $\text{RH} = 85\%$).

Table B illustrates that when the full spectrum of climate conditions (solar radiation, driving rain, etc.) are considered, vapor drive behavior is not easy to predict. For example, whereas we would expect the vapor drive to be directed towards the exterior (positive net vapor pressure) when $\text{DT} = +30^{\circ}\text{F}$ and $\text{DRH} = -30\%$, it is not the case here. The magnitude of the net vapor pressure is also generally much smaller than with previous cases run with the basement slab. In the summer, the vapor drive is directed generally towards the exterior, and, in the winter, the opposite is true. These models suggest that solar radiation, driving rain, and other climate events do have a meaningful effect on vapor drive in unconditioned environments. Further

studies would need to be done to simulate assembly performance in specific climate environments in order to develop the suite of practical design tools that can be applied to these conditions.

DISCUSSION

Vapor drive is affected by many interrelated and interdependent variables. When

most of these variables can be controlled, as in coating installations in conditioned or relatively stable environments, it is possible to simplify the models or even rely on empirical evidence and experience to guide decisions. As the environments and assemblies get more complex and/or variable, simple models or rules of thumb are not as effective, and more complex modeling may be needed.

Fortunately, the tools for this modeling are already available for most assemblies. This is not inconsistent with modeling already performed in other contexts. In some designs, it may follow naturally from energy modeling already performed for

other purposes. These analyses, used in conjunction with the considerations shown in Figure 6, can provide a rational basis with which to assess expected coating performance.

An important parameter not yet discussed herein is the introduction of moisture into the concrete due to the hydration process or other sources. Our models would

Example Coating Installation Decision Guide

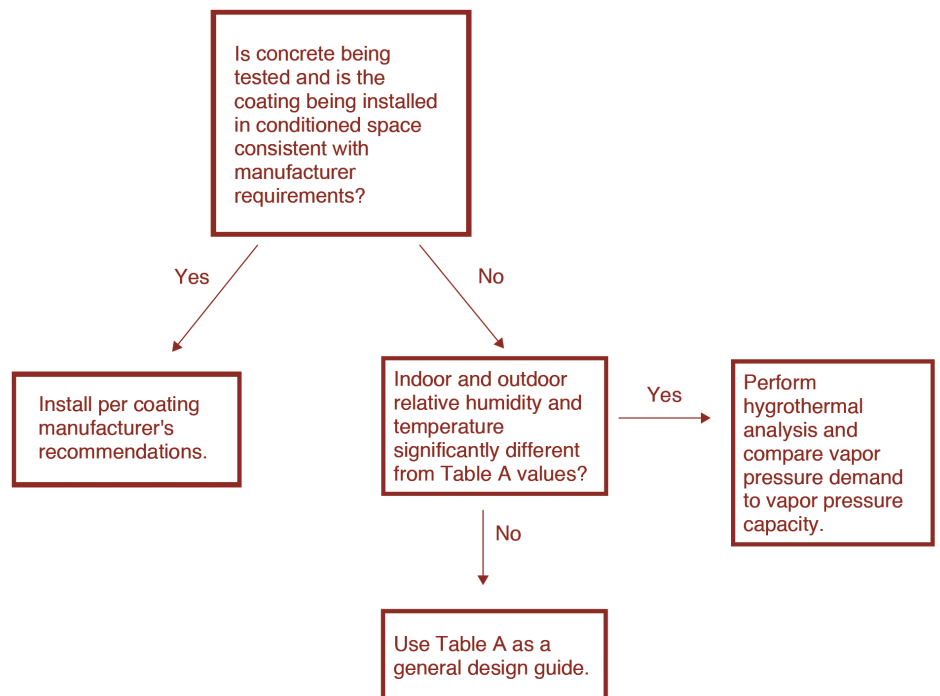


Figure 6 – An example of a coating installation decision guide to be used in conjunction with example design guide table for concrete slabs on ground.

		$\Delta T (T_{\text{concrete}} - T_{\text{air}})$													
		-50F	-40F	-30F	-20F	-10F	0	+10F	+20F	+30F	+40F	+50F			
$\Delta RH (RH_{\text{concrete}} - RH_{\text{air}})$	-40%	ok by inspection	ok by inspection	ok by inspection	ok by inspection	ok by inspection	ok by inspection	-0.068	-0.025	0.029	0.077	0.108			
		-0.068	-0.035	-0.002	0.041	0.064	-0.021	-0.006	0.013	0.022	0.029				
		0.000	0.065	0.094	0.120	-0.043	-0.045	-0.012	0.029	0.056	0.075				
	-30%	ok by inspection	ok by inspection	ok by inspection	ok by inspection	ok by inspection	ok by inspection	-0.043	0.000	0.065	0.094	0.120			
		-0.043	-0.012	0.029	0.056	0.075	-0.013	0.001	0.020	0.025	0.031				
		0.025	0.100	0.111	0.132	-0.017	-0.021	0.011	0.058	0.071	0.085				
	-20%	ok by inspection	ok by inspection	ok by inspection	ok by inspection	ok by inspection	ok by inspection	-0.017	0.025	0.100	0.111	0.132			
		-0.017	-0.021	0.011	0.058	0.071	-0.005	0.008	0.025	0.028	0.033				
		0.005	0.020	0.045	0.045	0.051	ok by inspection	ok by inspection	ok by inspection	ok by inspection	ok by inspection				
	-10%	ok by inspection	ok by inspection	ok by inspection	ok by inspection	ok by inspection	ok by inspection	0.017	0.070	0.181	0.168	0.186			
		0.017	0.070	0.181	0.168	0.186	0.009	0.050	0.127	0.119	0.130				
		0.005	0.020	0.045	0.045	0.051	0.042	0.096	0.217	0.186	0.198				
0%	ok by inspection	ok by inspection	ok by inspection	ok by inspection	ok by inspection	ok by inspection	0.042	0.096	0.217	0.186	0.198				
	0.042	0.096	0.217	0.186	0.198	0.033	0.073	0.159	0.135	0.142					
	0.013	0.027	0.051	0.048	0.053	-0.070	-0.094	-0.175	-0.079	-0.018	0.025	0.076	0.141	0.298	0.242
10%	-0.070	-0.094	-0.175	-0.079	-0.018	0.025	0.076	0.141	0.298	0.242	0.252				
	-0.087	-0.112	-0.170	-0.061	-0.010	0.024	0.064	0.113	0.228	0.182	0.185				
	-0.101	-0.128	-0.070	-0.028	-0.006	0.009	0.024	0.041	0.073	0.067	0.071				
20%	-0.070	-0.094	-0.118	-0.028	0.018	0.051	0.102	0.166	0.334	0.260	0.264				
	-0.087	-0.107	-0.081	-0.013	0.024	0.048	0.088	0.137	0.260	0.199	0.196				
	-0.101	-0.061	-0.036	-0.009	0.007	0.018	0.032	0.047	0.079	0.070	0.074				
30%	-0.052	-0.070	-0.076	0.000	0.045	0.076	0.136	0.212	0.417	0.318	0.319				
	-0.065	-0.080	-0.038	0.015	0.050	0.073	0.121	0.179	0.334	0.249	0.243				
	-0.077	-0.049	-0.022	0.002	0.019	0.030	0.047	0.066	0.106	0.093	0.096				
40%	-0.035	-0.047	-0.034	0.028	0.072	0.102	0.170	0.258	0.499	0.375	0.374				
	-0.043	-0.054	0.004	0.044	0.077	0.098	0.153	0.220	0.403	0.298	0.288				
	-0.053	-0.037	-0.008	0.014	0.030	0.042	0.062	0.084	0.132	0.115	0.118				

Net Vapor Pressure (psi)
1 hour
24 hours
1 year

Table A – A design guide table for 4-inch-thick basement slab on ground with 0.1-perm coating.

capture latent moisture from cured concrete that has already hydrated, but do not account for the introduction of moisture during the modeling period. For relatively young concrete, this could be quite easily included in the model once the hydration moisture levels are quantified.

A reproducible framework for future expansion of the analysis begun here has been provided. As hygrothermal analysis becomes more prevalent in the future, access to a larger pool of data may be available with which the design guide tables proposed herein (or an app) could be further developed and refined. Even if a suite of tables were developed only for a limited set of the most commonly encountered conditions and assemblies, the industry would benefit greatly from efficient use of

these tools and increased understanding of the subject.

Design specifications can also be simplified greatly if—instead of specifying the temperature and RH of the exterior, the interior, and the concrete—the net vapor pressure capacity is specified as the design parameter. Since the net vapor pressure capacity of a coating is a material property that should not be significantly affected by envi-

ronmental conditions, designers can assess expected coating performance regardless of construction conditions. Consideration could be given to providing multiple allowable vapor pressures: one for early age during the curing phase, when the coatings are more sensitive and conditioning should be managed more carefully; and another for a fully cured coating that may be more tolerant to higher vapor pressures, allowing

		$\Delta T (T_{\text{concrete}} - T_{\text{air}})$			
		-30F	-20F	+20F	+30F
$\Delta RH (RH_{\text{concrete}} - RH_{\text{air}})$	-30%				-0.00439
					-0.07828
					-0.06833
	-20%		0.000653	-0.00282	
			0.03297	-0.0401	
			0.112658	-0.01967	
+20%		0.00041	-0.00353		
		0.00722	-0.03652		
		0.01196	0.033423		

Vapor Pressure (psi)
1 hour
24 hours
1 year

Table B – Partial design guide table for 8-inch-thick insulated roof deck with 0.1-perm coating.

more accommodation for service life variations and extremes.

Ultimately, it is hoped that manufacturers will publish the allowable net vapor pressure capacity for each coating so that this rational evaluation can be conducted. Most already do this implicitly by specifying maximum MVER or RH values for a specific material in a given environment from which net vapor pressure can be derived.

Note the vapor pressure capacity is very different from the bond strength. Bond strength is an instantaneous measure of bond capacity at a moment in time. Vapor pressure capacity is the time-dependent ability of the material to resist long-term low-level pressures imposed by moisture emission, which causes most failures.

RECOMMENDATIONS

Recommendations are separated into three categories, as shown on page 27. The first is for current designers seeking insight into the expected performance of a given concrete coating. The second category consists of recommendations for modifications to current industry practice. The third category is for future studies and research to improve the state of knowledge of moisture in concrete and associated coating performance.

Current Designs

1. Assemble appropriate parameters to include concrete thickness, concrete moisture levels, coating permeance, and expected environments on each side of the coating while in service.
2. Follow *Figure 6* example flowchart. If analyses are required, consider more advanced analysis to include computer modeling of assembly and environmental conditions, or design guide tables if available.
3. If analyses show net vapor pressure over service life is less than that allowed by or derived from manufacturer's literature, the coating should perform acceptably. If not, revise design.
4. Continue to follow current practices for coating installations (mat tests, mock-ups, etc.).

Industry Practice

1. Publish allowable vapor pressures for coatings to facilitate analyses of expected performance.
2. Develop design guides similar to


Tables A and B for use in common applications.

3. Assemble empirical data, including conditions leading to coating failures, so better insight into expected performance can be established.

Additional Study

1. Perform more analytical studies to further explore the various parameters and their effects on net vapor pressure, including the effects of

concrete hydration.

2. Conduct laboratory testing of physical models to evaluate the design approach and proposed acceptance criteria. 

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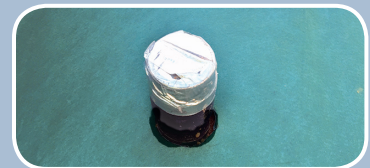


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