A NEW LOOK AT MOISTURE CONTROL IN LOW-SLOPE ROOFING

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One of the criteria for a moisture-tolerant roof is 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. Failing this criterion would require the inclusion of a vapor retarder into the roof system. This requirement was tested using computer simulations for a series of new roof systems and environmental conditions.[1]

This paper uses the database from those simulations to develop a simplified method to predict condensation control using only variables associated with the roof and environmental conditions. This method assesses the potential for condensation within the roof assembly without having to perform a computer simulation.

Using the computer simulation output data, the moisture accumulation inside each of the roof systems was calculated. A critical threshold of moisture accumulation was assigned by analyzing the roof systems that fail to prevent condensation from occurring within the roof system.

An empirical equation for moisture accumulation as a function of roof system and environmental condition variables is developed. The moisture accumulation calculated using this relationship correlates well with the moisture accumulation based on the results of computer simulations. The ability of these two different relationships for moisture accumulation to predict condensation control using the established critical threshold is assessed. Accuracy of both methods is more than 95 percent.

KEYWORDS

Computer simulation, low-slope roof, moisture, moisture control, vapor pressure, vapor retarder.

INTRODUCTION

Moist and dripping roofs have no doubt been a problem since the time humans took up residence in caves. In a more contemporary context, moisture accumulation, particularly in low-slope roofing, has become a multimillion dollar problem in the United States.[2]

Moisture accumulation in roof systems can create a number of costly problems, including dripping, accelerated insulation and membrane failure, the threat of roof structure deterioration, depreciation of assets, and poor thermal performance. Moisture accumulation can severely impact the thermal performance of insulation in a roof system. It is estimated that energy losses through roofs in the United States are increased by approximately 70 percent because of the loss of the insulation's thermal resistance due to moisture.[2] Wet roofing must be replaced at significant cost, both financially and in terms of increased construction waste.[2]

Clearly, the potential cost saving of an effective and efficient roof system is great. Intuitively, the response to the problem of moisture accumulation in roofs has been to try to limit as much as possible the inflow of moisture, for example, by improving the reliability of roofing membranes. However, as Kyle and Desjarlais point out, "... most roofing systems inevitably leak." For this reason, they suggest that the best strategy for reducing moisture accumulation is through designing moisture-tolerant roofs, which incorporate reliable ways of improving moisture flow out of the roof.[2]

This strategy was suggested by Powell and Robinson's studies of the effects of water on roof systems in the 1970s.[3] In their view, designs for insulated moisture-tolerant flat roofs would be "the most practical and economic" solution to the problems created by moisture accumulation.

To determine whether a specific roof system is moisture-tolerant, roofing designers require accurate but convenient and cost-efficient analytical tools for evaluating their roof designs. One such tool is computer modelling. We have used finite difference computer modelling to demonstrate the effectiveness of moisture-tolerant roof designs in several different climate zones in the United States.[1] However, setting up the necessary data files, running a finite difference simulation, and interpreting the output requires computer skills and very specific technical knowledge that limits the widespread usefulness of this tool. A simpler, readily available technique for assessing the suitability of different moisture-tolerant roof designs would also be useful as a practical guide in selecting appropriate materials and designs for these roofs.

This paper describes the development of such an analytical tool, based on the authors' earlier work. Using the computer simulation data as a starting point, a method is developed for predicting the condensation potential of different new roof designs using an algorithm requiring only the variables associated with components of the roof system and the interior and exterior climate. This algorithm can then be included in a fast, user-friendly computer program that will be accessible to a much wider user group. The capability of predicting condensation potential will allow the roofing designer to assess the need for a vapor retarder for a particular roofing design or allow the designer to engineer the roof system so that a vapor retarder is not required. This will enable a roofing professional in the United States to quickly and accurately determine if a roof constructed with a given type of membrane, insulation material and deck will be moisture-tolerant in a given location and indoor relative humidity, without the need to set up and run a computer simulation.

This paper reports on an element of the authors' moisture tolerance research that has been ongoing for more than six years. References 1, 2, 4, 9, 10 and 11 have described, validated and used the model on low-slope roofing applications. These references describe in detail the model that is used, the limitations of the model and sources of material property data. Other requirements for a moisture-tolerant roof are described in Reference 1, including the need for the roof system to be capable of eliminating moisture transport by convection and handling water leaking into the roof through imperfections in the membrane.

MOISTURE-TOLERANT ROOF REQUIREMENTS

A moisture-tolerant roof is defined as "a roofing system which is designed to minimize the deleterious effects of water accumulation."[2] A moisture-tolerant low-slope roof design can be achieved by selection of roofing characteristics and materials appropriate for a given set of environmental conditions. Characteristics of the roof design that can be adjusted to offer increased moisture tolerance include the solar absorptance of the membrane, the type, permeance, and thickness of the insulation material, and the permeance of the deck material.

Moisture-tolerant roof design

Some elements of the moisture-tolerant roof were established by the work of Powell and Robinson.[3] In simplified schematic form, a roof can be modelled for moisture tolerance in five sections. (See Figure 1.) The membrane represents the "outer" part of the roof, which is in direct contact with weather and environmental conditions such as sun, rain and wind. Next are layers of insulation, modelled in three sections; an outer section adjacent to the membrane, a core and an inner section next to the deck. The deck is the "inner" part of the roof, which is in contact with the interior of the structure. Note that the modelling of the insulation material in three layers is simply an issue of convenience. The authors are interested in how moisture moves within the insulation material and the division of that material into at least three layers allows for monitoring of the moisture distribution. These three layers may be composed of portions of a single piece of insulation or three completely separate materials as in a composite insulation system.

Winter uptake and condensation

A set of requirements for predicting if a roof system will be moisture-tolerant has been documented.[1] One of these requirements is that during the winter, when uptake of water vapor from the interior of the building into the roof system typically occurs, 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. Because the membrane is the coldest portion of the roof system during winter, condensation must occur under the membrane before it does at any other location in the roof system. Effectively, this requirement tests the need for a vapor retarder. The computer simulation uses a finite-difference heat and mass transfer model[4] to test this requirement for different new roof system configurations. The results are evaluated to ensure that the relative humidity of the insulation layer just below the membrane (the outer insulation in Figure 1) does not reach 100 percent, which would indicate that condensation has occurred. The choice of three layers of insulation material allows us to focus on localized moisture conditions just under the membrane by defining one layer as being a thin portion of the insulation just below the membrane.

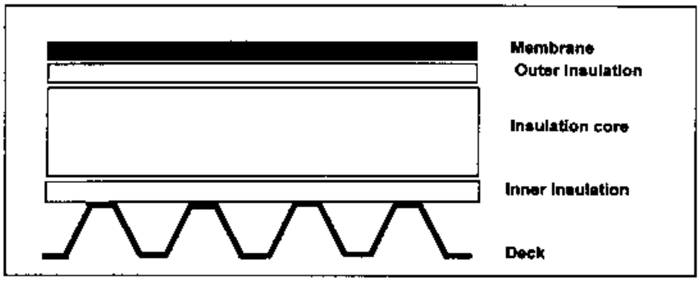

Figure 1. Roof schematic used for modelling purposes.

ESTABLISHING CORRELATIONS BASED ON "NO CONDENSATION" CRITERION

The authors have analyzed 120 new roofing configurations for each of five different cities according to this "no condensation" criterion. The first objective in this paper was to use this database to develop correlations for moisture accumulation as a function of the variables associated with the roof system and environmental conditions. If successful, this could be used as one element of a method for predicting if a given roof system would be moisture-tolerant without performing a computer simulation.

Description of the database

Most of the database used in the research described by this paper was generated in recently completed work.[1] One additional climate, Seattle, was added for this study. The original four climates studied represent the range of climates in the continental U.S. as measured in heating degree days: Bismarck, North Dakota; Chicago, Illinois; Knoxville, Tennessee; and Miami, Florida. Seattle, Washington, was added to determine if moisture control in a roof system installed in a coastal climate behaved differently from those installed in a continental climate. Indoor relative humidities of 40 percent, 50 percent and 60 percent were used in the study; the indoor temperature was held constant at 20°C (68°F). This combination of indoor conditions defined a range of indoor vapor pressures. Note that the work to date is not applicable for cold storage buildings or any other building whose interior vapor pressure falls outside of the simulated range of vapor pressures. The analyses performed to date ignore the effects of other parameters such as snow loads and the nat-

<table>
<tr><th colspan="4">Roof system properties</th></tr>
<tr><th>Insulation Type</th><th>Insulation Thickness, in (mm)</th><th>Membrane Absorptance</th><th>Deck Permeance, perms (g/Pa•s•m²)</th></tr>
<tr><td>Fiberboard</td><td>1 (25)</td><td>0.1 (black)</td><td>0.64 (3.6×10^{-8})</td></tr>
<tr><td>Polyisocyanurate(PIR)</td><td>3 (76)</td><td>0.7 (white)</td><td>1.0 (5.7×10^{-8})</td></tr>
<tr><td>Composite</td><td>3 (76)</td><td></td><td>5.0 (29×10^{-8})</td></tr>
<tr><td>(Fiberboard +PIR)</td><td></td><td></td><td>10.0 (57×10^{-8})</td></tr>
<tr><th colspan="4">Environmental conditions</th></tr>
<tr><th colspan="2">Climate (heating degree days)</th><th colspan="2">Building interior relative humidity, %</th></tr>
<tr><td colspan="2">Bismarck (8992)</td><td colspan="2">40</td></tr>
<tr><td colspan="2">Chicago (6151)</td><td colspan="2">50</td></tr>
<tr><td colspan="2">Knoxville (3818)</td><td colspan="2">60</td></tr>
<tr><td colspan="2">Miami (185)</td><td colspan="2"></td></tr>
<tr><td colspan="2">Seattle (5280)</td><td colspan="2"></td></tr>
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Table 1. Roof system properties and environmental conditions simulated.

ural variation in indoor vapor pressure due to seasonal change. The latter assumption has been studied[12] and has been found to not have a significant impact on the results as long as the average indoor vapor pressure is simulated.

The range of roof systems evaluated included 25-mm- and 76-mm-(1-inch- and 3-inch-) thick wood fiberboard, 25-mm and 76-mm (1-inch and 3-inch) polyisocyanurate (PIR) insulation, and a 76-mm (3-inch) composite of the two (a core of 51-mm [2-inch] polyisocyanurate foam sandwiched between layers of 13-mm [0.5-inch] fiberboard). Metal decks with water vapor permeances of 3.6, 5.7, 29 and 57 x 10-8 g/Pa•s•m² (0.64, 1, 5, and 10 perms) were included. Vapor permeance is provided through discontinuities such as burn holes, side and lap seams, and fastener penetrations. The two lower levels of deck permeance are from Reference 2. The remaining two higher levels are assumed values for decks that would be purposely perforated for moisture-control purposes. Two values for membrane absorptance (0.7 for a white roof and 0.1 for a black roof) were modelled. All possible combinations of the above parameters were simulated using the finite-difference model. Table 1 summarizes the roof properties and environmental conditions analyzed. Note that all of the roofing simulations were performed on new roofing configurations; reroofing applications are presently beyond the scope of this analysis, but not of the procedure.

All of the 600 configurations were evaluated according to the moisture-tolerant requirement. Roof systems that showed a relative humidity of 100 percent in the outer insulation layer just below the roof membrane were determined to fail the no condensation requirement.

DETERMINATION OF MOISTURE ACCUMULATION

Moisture moves into the roof system via vapor diffusion, air leakage, and gravimetrically through discontinuities in the insulation layer. Other requirements of a moisture-tolerant roof address the issues of moisture transport by air leakage and through cracks in the insulation; they must be eliminated.[1] If moisture transport is limited to diffusion, then the flow rate of water vapor into a roof typically occurs during the winter uptake period when the indoor vapor pressure is greater than the vapor pressure underneath the membrane of the roof. This creates a vapor pressure drive into the roof. The moisture flow rate is proportional to the magnitude of the difference in vapor pressures across the roof divided by the sum of the resistances to vapor diffusion.

$$\dot{m} = \frac{p_{vi} - p_{vm}}{R_{bl} + R_{d} + R_{i}} \qquad [1]$$

where $\dot{m}$ = mass flow rate of moisture into the roof, lb/hr ft² (kg/hr m²);

p_{vi} = indoor vapor pressure, psi (kPa);

p_{vm} = average vapor pressure directly under the roof membrane during the winter uptake months, psi (kPa);

R_{bl} = vapor resistance of the boundary layer of air under the roof deck, Reps (metric Reps);

R_{d} = vapor resistance of the deck, Reps (metric Reps); and

R_{i} = vapor resistance of the insulation, Reps (metric Reps).

These variables were determined in the following ways: The indoor vapor pressure can be determined by multiplying the saturation vapor pressure (found in any standard saturated steam table) at the indoor temperature of 20°C (68°F) by the relative humidity.[5] The vapor resistances of the insulation and the deck can be found by taking the inverse of the permeance (or by dividing the thickness by the permeability). Permeance and permeability values can be obtained from the *ASHRAE Handbook of Fundamentals*.[6] More complete listings of these parameters, including the impact of relative humidity, are available from the International Energy Agency.[7] The average monthly vapor pressure values directly under the membrane during winter uptake were extracted from the finite-difference simulations and averaged, to determine the average vapor pressure under the membrane during the winter uptake months. The number of months of winter uptake were counted to determine the length of time in which moisture accumulation occurs.

These values can be used in the relationship for moisture flow rate. Total moisture accumulation, m, is then found by multiplying the moisture flow rate by the number of months when the vapor drive is upward into the roof, t:

$$m = \dot{m}\, t \qquad [2]$$

ESTABLISHMENT OF PASS/FAIL THRESHOLD FOR EACH MATERIAL

The calculated values of moisture accumulation were listed in ascending order for each type of insulation material. Next to each value of moisture accumulation was the identifying roof system code and whether or not the roof system failed the stated condensation control requirement. These lists were examined to determine the thresholds of moisture accumulation where most roof systems begin to fail for each type of insulation. By comparing the moisture accumulation data to the simulation outputs that indicated whether condensation occurred, the critical thresholds were readily identified by determining what value of moisture accumulation indicated the onset of condensation. The critical thresholds of moisture accumulation were determined to be 0.06 kg/m² (0.012 lb/ft²) for polyisocyanurate, 0.69 kg/m² (0.14 lb/ft²) for the composite, and 1.0 kg/m² (0.20 lb/ft²) for the fiberboard.

DEVELOPMENT OF CORRELATION BASED ON INPUT DATA

It is desirable to be able to predict failure of a roof system using only the parameters associated with the roof system (i.e., materials and configuration) and environmental conditions without using a computer model for each new system evaluated. To this end, the second objective was to develop a correlation to predict moisture accumulation in terms of indoor relative humidity, heating degree days, deck permeance, and roof solar absorptance.

Multiple linear regression was done using combinations of first, second, third order and inverse terms of each of the four variables to develop correlations for average winter vapor pressure directly under the membrane and the length of time of the winter uptake period. Solar absorptance was shown not to affect the correlation for time of winter uptake. The results from Equations 4 and 5 were then inserted into Equation 3, moisture accumulation, that results in an equation that predicts moisture accumulation in terms of the parameters listed. These equations are seen below.

Moisture accumulation,

$$m = \frac{t(p_{vi} - p_{vm})}{R_{bl} + R_d + R_i} \qquad [3];$$

where $p_{vm} = -0.93414 + 0.284\phi + 4.850\text{x}10^{-4}H - 7.995\text{x}10^{8}H^2 + 4.215\text{x}10^{-12}H^3 - 2.053\text{x}10^{-5}H\phi + 161.0/H + 0.002305P - 8.013\text{x}10^{-5}P^2 - 1.343\text{x}10^{7}HP - 0008889\alpha$ [4];

$t = -66.1 - 1.514\phi + 0.03390H - 5.655\text{x}10^{6}H^2 + 3.067\text{x}10^{-10}H^3 + 0.004424H\phi - 4.327\text{x}10^{7}\phi H^2 + 11430/H$ [5];

and p_{vm} = average vapor pressure just below the membrane during the winter uptake period, (lb/in²);

t = length of time of winter uptake (months);

ϕ = indoor relative humidity;

H = climate heating degree days (°F);

P = deck permeance (English perms); and

α = membrane solar absorptance.

A value of 0.0211 Reps was used for the vapor resistance of the boundary layer of air beneath the deck.[6]

The average winter vapor pressure under the membrane proved to be strongly influenced by the indoor relative humidity and climate. It tended to decrease as the climate became colder, yielding larger vapor pressure differences across the roof system. Solar absorptance of the roof membrane and deck permeance were found to have a weaker effect on average winter vapor pressure.

For the length of time of winter uptake, relative humidity and heating degree days were again the significant influences. The period of winter uptake tended to increase with relative humidity and colder climates. Deck permeance had a minor effect, and membrane absorptance was found not to be a factor.

Roofing configurations with no moisture accumulation did not experience a winter uptake, but a vapor drive out of the roof system and year-round drying. Because Equation 3 is not valid for determining moisture removed, these systems were excluded from the data used to generate the correlation. However, these systems were added back into the pool of data after the correlation was done so that they could be included in the evaluation of the method. The results for these systems were near zero values of moisture accumulation.

Comparison of Simulation-based Moisture Accumulation and Correlation-based Moisture Accumulation

The moisture accumulation values calculated using this correlation were then compared to the moisture accumulation based on computer simulations. The correlation coefficient was 0.98 between the two. The plot can be seen in Figure 2. The slope of the best-fit line is 0.88, indicating that, on average, the input-based moisture accumulation is generally conservative in its estimation.

The final evaluation of the method is whether the results derived from the correlations using only the input conditions (correlation-based) and roof properties agree with the results from the computer simulations (simulation-based). Since data from 120 composite, 240 fiberboard and 240 PIR roofing systems and conditions were evaluated, the data is summarized by breaking the data for each insulation type into 12 groups and presenting an average value of moisture accumulation along with the predicted failures for each of the two methods. Although the listing of each individual simulation would be preferable and more clearly demonstrates the comparison between the methods, the groupings are depicted for brevity. The results are seen in Tables 2.1, 2.2 and 2.3. Note that the correlation-based results slightly underpredict the moisture accumulation as compared to the simulation-based results for the composite systems, but overpredict for the fiberboard and PIR systems.

The proposed new correlation is 97 percent accurate in predicting passing and failure of roof systems for the thresholds indicated above. The "worst case," a prediction of pass-

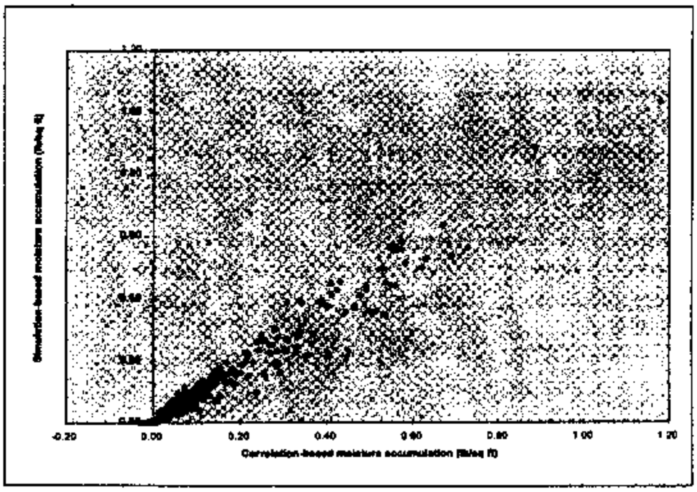

Figure 2. Simulation-based vs. correlation-based moisture accumulation.

Moisture Accumulation in Composite systems (Groups of 10) Failure Threshold = 0.14 lb/ft^2			
Correlation-based		Simulation-based	
Moisture Accumulation (lb/ft^2)	No. of Failures	Moisture Accumulation (lb/ft^2)	No. of Failures
-0.001	0	0.000	0
0.000	0	0.000	0
0.008	0	0.010	0
0.018	0	0.027	0
0.020	0	0.035	0
0.031	0	0.041	0
0.040	0	0.051	0
0.042	0	0.059	0
0.054	0	0.070	0
0.064	0	0.084	0
0.081	0	0.098	0
0.122	3	0.141	3

Table 2.1. Moisture accumulation in composite systems.

ing for a failing system happens in less than 1 percent of the 600 cases. Of these five cases, two occurred for "borderline" failures—systems for which the relative humidity at the membrane was above 100 percent for less than one month. The other three cases were all high (60 percent) relative humidity, cold climates (Bismarck and Chicago), 76-mm (3-inch) fiberboard systems. The reason these three failures were not accurately predicted is unclear.

SUMMARY AND CONCLUSIONS

The values of moisture accumulation calculated using the results of computer simulations substituted into Equation 3 were effective in predicting failure according to the "no condensation" moisture-tolerant roof requirement. Roof systems that have higher moisture accumulation failed the requirement. These results were used to establish critical thresholds for fiberboard, polyisocyanurate and the composite. The fiberboard roof systems have higher water absorbing capability and absorbed significantly higher moisture levels prior to the onset of condensation than the low absorptance polyisocyanurate insulation roofs.

Moisture accumulation in fiberboard systems (groups of 20) Failure Threshold = 0.20 lb/ft^2			
Correlation-based		Simulation-based	
Moisture Accumulation (lb/ft^2)	No. of Failures	Moisture Accumulation (lb/ft^2)	No. of Failures
-0.008	0	0.000	0
0.002	0	0.000	0
0.014	0	0.014	0
0.033	0	0.035	0
0.051	0	0.051	0
0.068	0	0.066	0
0.086	0	0.082	0
0.123	3	0.111	2
0.193	5	0.166	5
0.293	17	0.254	18
0.416	20	0.379	20
0.627	20	0.561	20

Table 2.2. Moisture accumulation in fiberboard systems.

Moisture accumulation in PIR systems (In groups of 20) Failure Threshold = 0.012 lb/ft^2			
Correlation-based		Simulation-based	
Moisture Accumulation (lb/ft^2)	No. of Failures	Moisture Accumulation (lb/ft^2)	No. of Failures
-0.002	0	0.000	0
0.002	0	0.000	0
0.006	1	0.004	3
0.016	14	0.010	14
0.025	17	0.018	17
0.031	20	0.025	20
0.037	20	0.031	20
0.047	20	0.039	20
0.057	20	0.047	20
0.072	20	0.062	20
0.100	20	0.086	20
0.178	20	0.158	20

Table 2.3. Moisture accumulation in PIR systems.

Good agreement was obtained between the values of moisture accumulation calculated from simulation-generated data and moisture accumulation calculated from the correlation of variables associated with the roof system and indoor conditions. Both methods of determining moisture accumulation using roof system properties and environmental conditions are more than 95 percent effective in predicting failure of a roof according to the stated moisture-tolerant requirement. This represents a huge improvement over current methods where condensation directly below the membrane is not usually assessed and a much greater number of roofs are being designed that fail this requirement for moisture tolerance.

The relationships presented can be used to effectively predict whether a roof system will fail the "no condensation" requirement for moisture-tolerant roof systems. This evaluation can now be accomplished without the use of a computer simulation. Simulations of the coastal climate of Seattle fit well with the continental climates; heating degree days appear to be an appropriate measure to track condensation potential for the entire United States.

FUTURE WORK

Similar correlations are being developed for the remainder of the moisture-tolerant roof requirements. These include a requirement that moisture will not leak into the building interior if a minor leak occurs through the roof membrane, and a requirement that drying time should be minimal after a leak occurs. In addition, the applicability of the correlation-based prediction algorithm must be tested to verify that it is appropriate to apply to other roofing systems containing other types of insulation and decks located in other climates with a wider range of indoor vapor pressures. Once these tasks are completed, the algorithms will be used as the basis of an Internet home page where roof designers will be able to assess the moisture tolerance of their roof designs by simply selecting the roof system components, the building location and interior conditions. The construction of this home page should be complete in late 1997.

ACKNOWLEDGMENTS

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