The Self-Drying Concept for Flat Roofs

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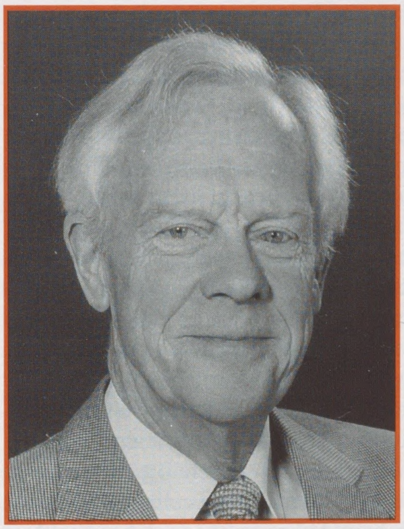

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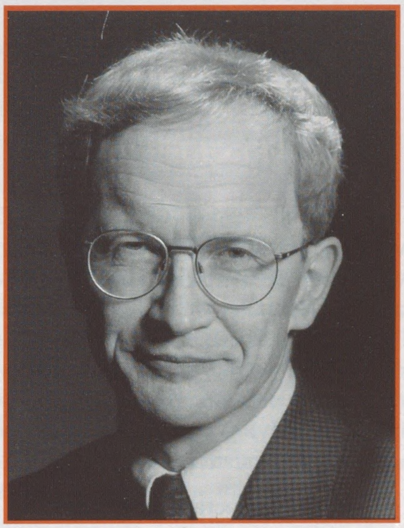

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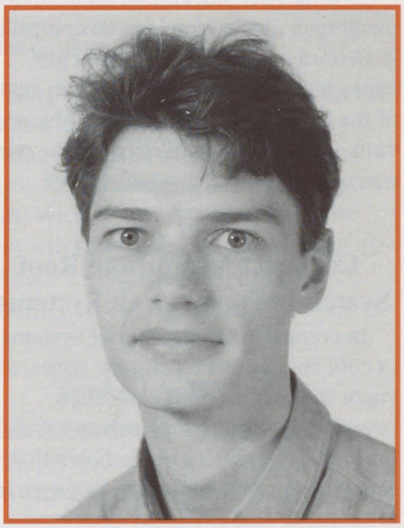

Carsten Rode

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Tommy Bunch-Nielsen has been a consulting engineer and managing director of Bygge-og Miljoteknik since 1987. He serves as manager of the Danish Roofcontractors Advisory Board and managing director of the Danish board that issues warranties on roofs. He is additionally a member of the Danish Code Committee and Roof Component Control Body. Mr. Bunch-Nielsen received his master's degree in civil and structural engineering from the Technical University of Denmark.

Carsten Rode authored the PC program MATCH for prediction of transient heat and moisture flow in building construction (discussed in this article). He has worked as senior researcher with the Danish Building Research Institute since 1992. Prior to that, he worked as a civil engineer in a private Danish firm and was a visiting researcher with the Roof Research Center at the Oak Ridge National Laboratory. He was awarded both a master's and doctoral degree (civil engineering and building physics, respectively) from the Technical University of Denmark and conducted post-doctoral research there from 1990 to 1992.

Introduction

Moisture in flat roof systems with an insulation layer has been a long-standing issue for the roof industry. It is unrealistic and too costly to try to prevent moisture from entering a roof assembly during its service life. The approach, therefore, should be to keep moisture levels low by providing a path for moisture to periodically escape. A design strategy that assumes roof assemblies may get wet and permits them to dry presents a more forgiving and perhaps less costly alternative.[1, 2, 3]

Moisture may enter a roof assembly in a number of different ways: 1) from the interior by diffusion and convection, 2) during construction from moist materials or rain, and 3) after construction, rain water may enter through leaks.

Moisture Control in Flat or Low-Slope Roof Assemblies

The basic components of a low-slope roof assembly are a waterproofing membrane, thermal insulation, and a supportive deck. Additional components may be added for specific reasons. For example an air/vapor retarder may be needed to limit vapor transport upward from within the building.

There are two basic roof systems: the *compact* and the *framed* system. In the compact roof system, the insulation is placed above the roof deck. In the framed system, insulation is below the deck, between the framing members.

In principle, moisture in an insulated membrane roof system can be controlled in two ways: 1) by installing an air/vapor retarder on the winter warm side of the insulation layer, and/or 2) by providing means for ventilation on the winter cold side of the insulation layer.

Compact Membrane Roof Systems (Warm Deck Systems)

In compact membrane roof systems in cold and temperate climate zones, a vapor retarder is usually installed between the supporting deck and the insulation. Experience has shown that, over their service life, such roof systems often suffer from moisture problems. The reason for this, sometimes called the "Bathtub Syndrome", is that rain water coming through leaks in the roofing membrane and sometimes already present during construction will be trapped between the two moisture-proof layers: the vapor retarder and the roof membrane.

Due to small driving forces, ventilation of the insulated space between the vapor retarder and the roof membrane has been shown to be ineffective. Furthermore, a membrane perforated with a field of breather vents contains many penetrations that may be flawed, allowing external moisture to enter the system.

Framed Membrane Roof Systems (Cold Deck Systems)

A framed roof system has its insulation below the deck, between the framing members.

Ventilated Cold Deck Systems

A conventional cold-deck roof system consists of plywood, chipboard, or tongue-in-groove boards nailed above wooden joists. The height of the joists will usually be determined by structural rather than insulation requirements. Typically, the insulation thickness is less than the height of the joists. The insulation is placed in the lower part of the cavity, leaving a void for ventilation between the insulation and the deck.

Cold outside air, which has low absolute humidity, will enter the voids through some vents and be warmed by the heat transmission from below, so that it can take up moisture before leaving the roof through other vents.

In cool or temperate climates, the temperature of the deck will often be low enough to cause condensation of interior water vapor that migrates to the underside of the deck. The condensation might cause rot or fungal attack on the wooden materials, particularly if the moisture content of the wood increases to 20% by weight or more in periods when the temperature is above 5 degrees C (41 degrees F).

To minimize or prevent moisture migration by diffusion into the roof system, a vapor retarder is installed below the insulation layer. To prevent moisture migration by convection, the vapor retarder should be installed with airtight joints, including overlaps.

Very often, an effective air and vapor barrier is difficult to achieve. One supplementary precaution that has been proposed for small roof areas with eave-to-eave distances of less than 10 meters, is to ventilate the roof void to the outside air by openings in the eaves, or for larger roofs, by placing roof vents at select distances. The idea is that cold outside air, which has low absolute humidity, will enter the voids through some vents and be warmed by the heat transmission from below, so that it can take up moisture before leaving the roof through other vents. If the roof is well insulated, the ventilation air is only slightly heated, and hence, its capability to remove moisture is also small. On clear nights, the ventilation air may even deposit moisture by condensation in the void.

For small roof areas, wind-induced pressure differences may ensure a sufficient ventilation rate through the eaves to prevent moisture problems if the air/vapor retarder is reasonably tight. For large roof areas, ventilation through the eaves, even when supplemented by roof vents, may not provide sufficient ventilation to prevent moisture problems. The reason is, that there may be inadequate pressure differences between the vents. Furthermore, in windy periods, roof vents create an under-pressure in the roof cavity relative to the indoor environment, thus promoting further intrusion of moist indoor air into the roof through unavoidable leaks in the air/vapor retarder. Therefore, in some countries with either a cold or a temperate, humid climate, the ventilated cold deck roof is regarded as a poor option.

However, flat, wood-based cold deck roofs are considered good, inexpensive and flexible solutions to roofs over commercial and institutional buildings. Today such roofs are typically pre-manufactured as cassettes under controlled conditions in a dry indoor environment. Logistical control ensures that the roof sections can be mounted over a building with a high likelihood of being dry from the beginning.

Unventilated Cold Deck Systems

Until recently, the unventilated cold deck roof system was not considered a viable option because of concern over cold deck moisture problems. Two sources of moisture are of concern. 1) Water vapor migration into cold deck roofs: This can be greatly reduced by adding a vapor retarder to the system and by omitting vent openings in the roof membrane. Even if joints and overlaps are imperfectly sealed, there is little total air pressure difference to transport room air into the cavity insulation because outside venting has been elimi-

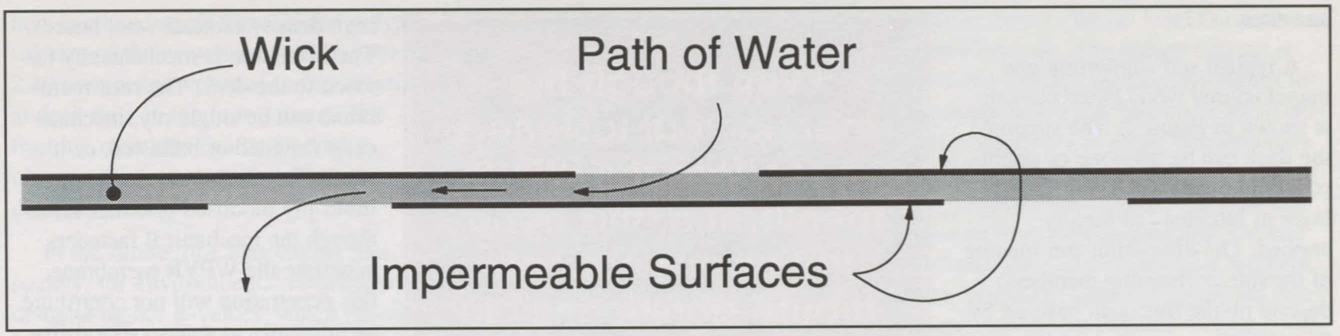

Figure 1. The Water Permeable Vapor Retarder

nated. Moisture migration due to diffusion, usually a minor source, can be greatly reduced even by a vapor retarder with only a moderate diffusion resistance. 2) Water from construction, leaks, and migrating water that accumulates: This can become trapped in the space between the two impermeable membranes — the roof membrane and the vapor retarder.

The Self-Drying Roof Concept

According to this concept, heat energy from spring and summer sun will evaporate winter- accumulated liquid moisture and drive it downward through a vapor-permeable deck into the building interior, where it is then evacuated.

A consequence of the requirement for a vapor permeable deck is that the concept cannot be applied in climate zones where a vapor retarder is needed to prevent unacceptable winter- accumulation of moisture. As stated by Kyle and Desjarlais: "Omission of the vapor retarder or impermeable layers such as an asphalt mopping to adhere two insulation layers together is a key to a self-drying roof. In situations where a vapor retarder is deemed essential, self-drying roof principles are violated".[4]

However, this dilemma can be solved by replacing the traditional waterproof vapor retarder with a water permeable vapor retarder (WPVR). One such WPVR, Figure 1 [5], consists of a synthetic fabric with good capillary suction properties sandwiched between strips of diffusion tight plastic film. The strips are staggered with an overlap. The size of the overlap and the thickness of the fabric, together with the permeance of the plastic film, determine the permeance of the WPVR [6, 7, 8].

The WPVR membrane can be considered as a hygro-diode, since it stops moisture in the form of water vapor (usually coming from below) but allows moisture in the form of construction water, leaked, or condensed water to wick through. This also has an advantage in allowing leakage to show up almost immediately and near to the point of entry.

The permeance of the WPVR can be tailored to different climate zones by varying the width of the plastic film strips, the overlapping and the thickness of the wick fabric. A typical embodiment will have a permeance of about 10 ng/(m^2 • s • Pa)(equivalent to 0.18 Perm).

Typical Self-Drying Membrane Roof Assemblies

To prevent moisture intrusion by convection one should make use of the totally air proof membrane by omitting breather vents and sealing all penetration flashings.

Unventilated Cold Deck Systems

Since ventilation is unnecessary, the space between the deck and the ceiling can be totally filled with insulation material. Thus, the unventilated cold deck system can have a very high R-value. It is also especially well suited for prefabrication in the form of closed

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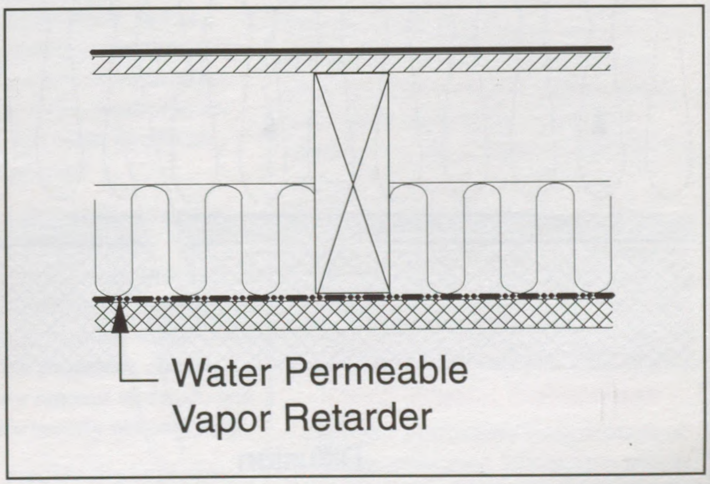

Figure 2. Unventilated Self-Drying Cold Deck Roof System.

cassettes.

A typical self supporting pre-manufactured wood based cassette is shown in Figure 2. The supporting deck can be plywood or oriented strand board (OSB) with a first layer of bitumen felt factory applied. The dimension and spacing of the rafters (framing members) depend on the free span covered by the cassette.

The thickness of the insulation is determined by the specified R-value. The insulation material will usually be relatively inexpensive, fire resistant, low-density fibrous glass or rock wool. The WPVR is supported by permeable ceiling panels such as wood-wool-cement or gypsum boards.

Unventilated Warm Deck Systems

A typical compact warm deck system is shown in Figure 3.

Even though the mechanical fasteners penetrate the WPVR membrane, this penetration will not contribute significantly to water vapor diffusion into the roof cavity.

The most commonly used types of structural decks are corrugated steel, precast or in- situ cast lightweight or reinforced concrete, or wood-panel decks. The WPVR is loosely laid with an overlap directly on the deck. Taping is not necessary, as the roof membrane constitutes the main air barrier. The insulation can be rigid foam boards or high density mineral wool boards. The insulation is mechanically fastened to the deck. The roof membrane can be single ply, mechanically fastened or ballasted, or it can be fully adhered, single or multi-ply modified bitumen. Even though the mechanical fasteners penetrate the WPVR membrane, this penetration will not contribute significantly to water vapor diffusion into the roof cavity.

Hybrid Cold - Warm Deck Roof Assembly

A hybrid cold - warm deck roof system is similar to the system shown in Figure 2 with the exception that the cassettes are not self-supporting. On top of the structural deck are fastened, pre-manufactured wood based cassettes.

As these cassettes are supported by the structural deck, the framing mem-

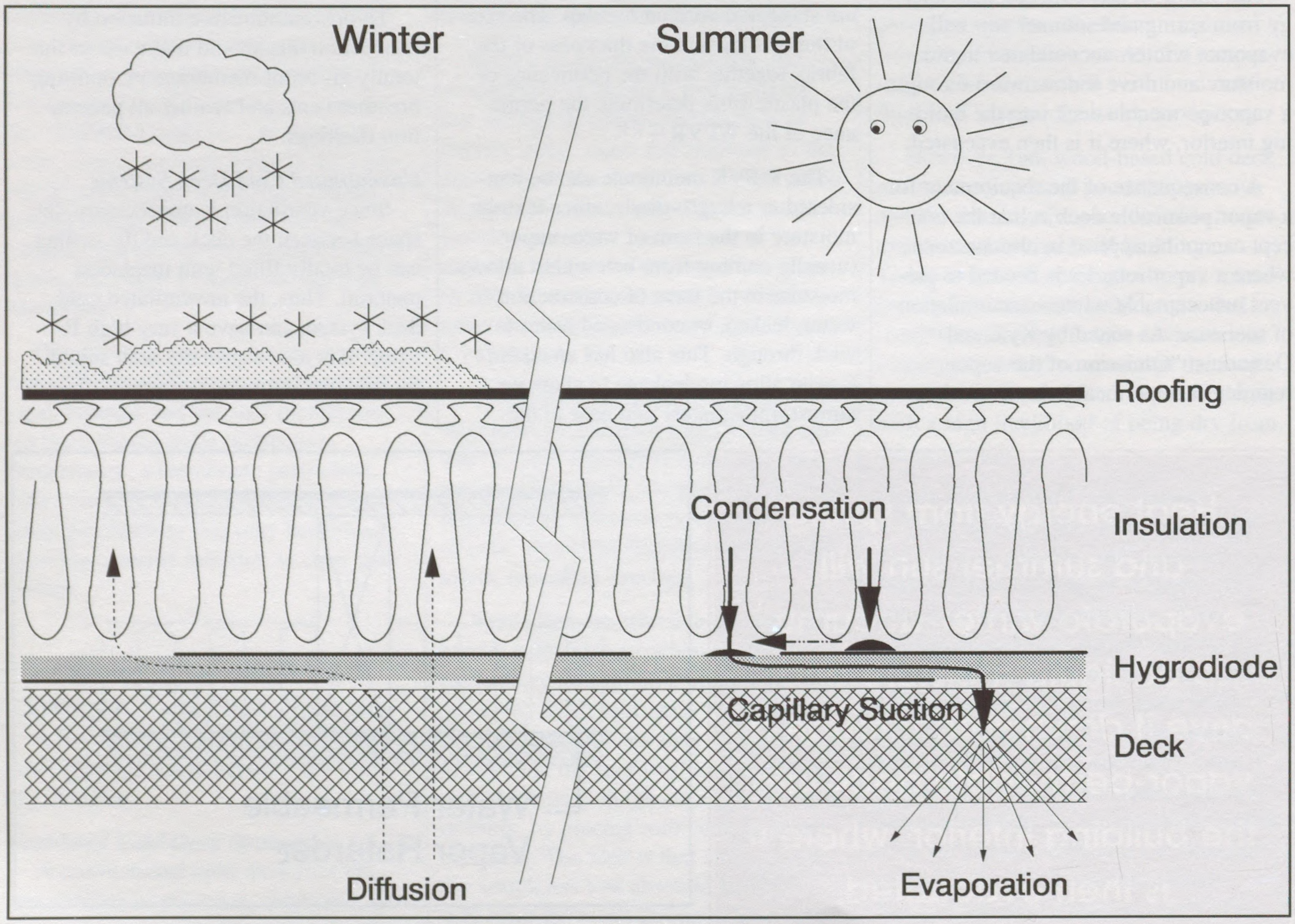

Figure 3. Unventilated Self-Drying Warm Deck Roof System.

bers can have small dimensions. A typical size of the cassettes could be 2.40 by 2.40 meters and fastened to the structural deck only in the four corners. The framing members can be tapered to obtain sufficient slope for effective drainage of rain water.

In the future, one may expect that society, for environmental reasons, will demand higher R-values, which means greater insulation thicknesses. In this cassette system, cheap low-density insulation materials can be used, as they will not take on any load or withstand roof traffic.

The light-weight cassettes are also suitable in retrofitting when tear-off is necessary due to wet insulation. For the self-drying roof concept to work, the old structural deck should be cleared of any vapor retarder. It can then absorb any moisture migrating out of the new cassettes.

The Match Program

In order to simulate with a high degree of accuracy the hygrothermal conditions within roof systems like the ones presented in the previous section, a transient model for combined heat and moisture flow will be needed. The program presented here, MATCH (Moisture and Temperature Calculations for Constructions of Hygroscopic Materials), was originally developed as part of a doctoral project[9]. Throughout and since the doctoral work, the program has been used to analyze the hygrothermal performance of constructions with hygroscopic materials in a number of research projects[10, 4, 11]. Furthermore, the program is used by a number of European building designers and manufacturers of building products.

Basic Transport Equations Used

The transient transport equations used in the program are the following.

For calculation of the temperature distribution:

$$\rho c \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left[k \frac{\partial T}{\partial x}\right] + \Delta h_v \frac{\partial}{\partial x}\left[\delta_p \frac{\partial p_v}{\partial x}\right]$$

For calculation of the moisture distribution:

$$\rho \frac{\partial u}{\partial t} = \frac{\partial}{\partial x}\left[\delta_p \frac{\partial p_v}{\partial x}\right] + \frac{\partial}{\partial x}\left[K \frac{\partial P_l}{\partial x}\right]$$

where:

c	=	Specific heat, J/(kg•K)
T	=	Temperature, K
t	=	Time, s
x	=	Length coordinate, m
u	=	Moisture content, kg/kg
ρ	=	Density of the material, kg/m^3
k	=	Thermal conductivity, W/(m • K)
Δh_v	=	Phase conversion enthalpy, water-vapor, J/kg
δ_p	=	Water vapor permeability, kg/(m • s • Pa)
p_v	=	Water vapor pressure, Pa
K	=	Hydraulic conductivity, kg/(m • s • Pa)
P_l	=	Capillary water pressure, Pa

In these equations, the most important way in which the temperature distribution affects moisture flow is through its influence on the vapor pressure distribution.

Implementation

The two equations have been implemented in the MATCH program using a control volume method with finite difference approximations of the partial derivatives, and are solved using an implicit calculation scheme. This scheme is numerically stable and is solved without iteration using time steps of one hour. The reader is referred to Rode Pedersen for more detailed questions on how the two basic equations have been implemented.[9]

The program comes with a database of parameters that describe how the material properties vary with temperature and moisture content. The properties are described in variably sized tables and thus, the properties can be described with any amount of detail, and the user can easily specify his own data.

The program predicts the hygrothermal conditions of assemblies that separate an indoor climate from the outdoors (see Figure 4). The indoor climate is described simply by monthly values for air temperature and humidity: either relative humidities or vapor concentration differences between indoor and outdoor air. The outdoor climate will typically be read from a meteorological file and includes such data as dry bulb temperature, humidity, solar radiation, and wind speed, so that the exterior surface conditions can be predicted quite accurately.

The program makes rather quick calculations of the governing equations. A one year simulation of a typical construction can be done in around 1 minute.

Validation Work

Since the program is available to a wide group of users, there is a continuing necessity to collect and disseminate knowledge of validations against as complex and well described experiments as possible. So far, in order to validate the program, a number of comparisons of its predictions to experimental results have been carried out. Some of these comparisons are given in the references by Rode Pedersen mentioned previously.

A recent validation of the program against detailed measurements of moisture content in a number of typical U.S. wall assemblies has recently been published. The experiment measured not only heat flux through the walls and moisture content of their wooden parts, but also determined the basic transport properties of the individual materials. Therefore, the experiment was very well suited for validation purposes. Very good agreement between model predictions and experimental results was obtained, e.g. δ_{RMS} values of around 1% moisture content by weight were obtained for the wooden layers of all walls[12].

Analysis of Flat Roofs and Vapor Retarders

In order to simulate the processes of winter accumulation of moisture and its drying in subsequent spring and summer

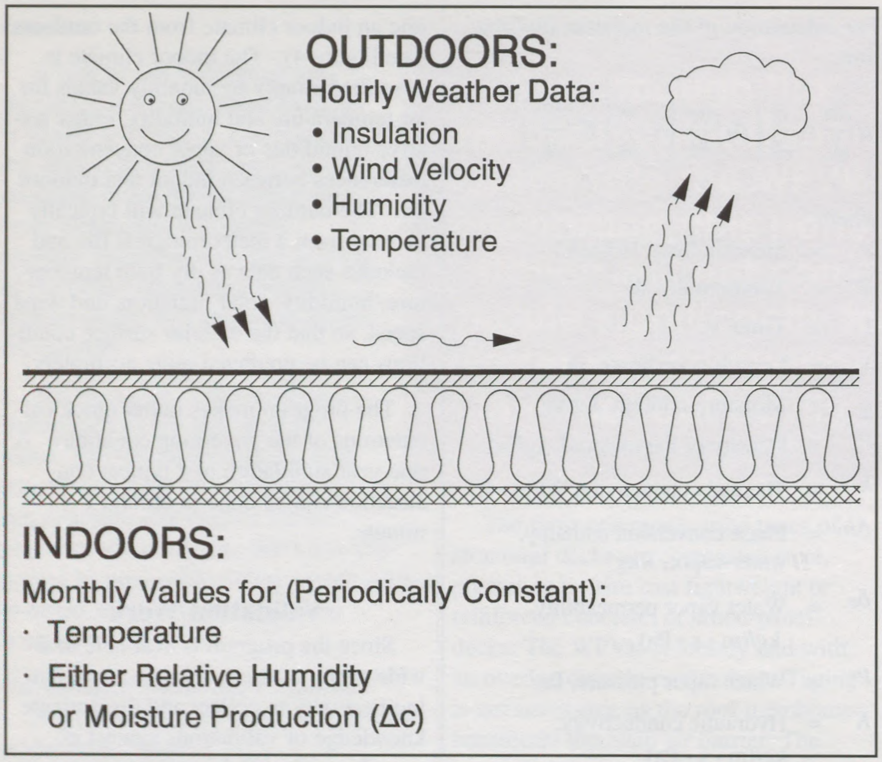

Figure 4. Indoor and outdoor climatic conditions considered by the MATCH program.

periods, it is necessary to predict with a high degree of accuracy the number of hours when conditions are such that condensation forms on the WPVR so the roof can dry. A transient program like MATCH is the only way to predict this.

Simulations of Cold Deck Roof Systems

To illustrate this, a flat cold deck roof like the one shown in Figure 2 will be analyzed in each of three cases:

- The roof has no vapor retarder.
- The roof has a traditional polyethylene vapor retarder.
- The roof has a WPVR.

In each case, the construction is simulated for the Danish outdoor climate (a coastal climate with about 3000 heating degree days (C) average air temperature close to the freezing point during the three coldest winter months, and mean air temperature in July: 16-17 degrees C). The indoor temperature is 21 degrees C (68 degrees F) — slightly higher in summer — and the indoor vapor concentration is set to be the same as in the outdoor air plus a moisture release of 3 g/m^3 slightly less in summer. The initial moisture content of the plywood deck is 20% by weight, i.e. the limit above which there is a risk that a fungal attack may commence.

Figures 5, 6 and 7 (see page 29) show the predicted moisture content for the internal layers of the construction in each of the three situations:

No vapor retarder (Figure 5): In this case there is a large influx of moisture during winter which is compensated by a large out-flux during summer. Whether or not there will be a net accumulation depends entirely on the climatic conditions. But even during one winter only, the plywood will become too moist and there is a risk that it will deteriorate.

Polyethylene vapor retarder, (Figure 6): With a polyethylene vapor retarder the moisture that dries out of the of the plywood in summer accumulates on the vapor retarder, i.e. the bottom of the insulation (legend RW39) is somewhat water logged during this period. Thus, the total moisture content stays almost the same throughout the year when a polyethylene vapor retarder is used. Only in the very long run will the conditions depend upon the climatic conditions that surround the construction — or it could be determined by flaws that might turn up.

Water Permeable Vapor Retarder (Figure 7): With the WPVR, the moisture content stays constant during winter because it works as a vapor retarder. But in summer it can be seen how excess moisture from the plywood first migrates to the WPVR (legend HDM) which then takes care of transporting the moisture out of the roof. In the next winter the moisture content remains constant again — but this time at a lower level.

Simulations of Warm Deck Roof Systems

In a similar fashion, two warm deck roofs like the ones shown in Figure 3 have been analyzed. From the inside, both roofs consist of a 80 mm concrete deck, 150 mm mineral wool insulation, and a water and vapor tight roof membrane on the top. Again, the roofs have either no vapor retarder, a polyethylene vapor retarder, or a WPVR. To simulate a situation with construction moisture, the concrete starts with a moisture content of 4.5% by weight (8.6 kg/m^2) and the insulation has a moisture content of 1 kg/m^2.

No vapor retarder (Figure 8): In this case, about half of the construction moisture from the concrete dries into the insulation (legend RWABB) which is quite wet throughout the first winter. The insulation dries out completely during the first summer, but in the next winter, a noticeable amount of moisture returns to the insulation.

Polyethylene vapor retarder (Figure 9): With a polyethylene vapor retarder the moisture content of the insulation layer stays constant, i.e. the construction moisture cannot dry out from here. The concrete dries out at a slower rate than in the case without a vapor retarder, because only downward drying is possible.

Water Permeable Vapor Retarder (Figure 10): With the WPVR, the construction moisture from the concrete is prevented from entering the insulation layer. Nevertheless, construction moisture from the insulation layer itself dries out during the first summer. Notice how the WPVR (legend HDM) becomes wet while the insulation layer dries out.

Quality Assurance of Roof Cassettes

In 1989, the main manufacturers of roof cassettes in Denmark joined to start up an organization to control the quality of manufactured roof cassettes. The organization is managed by neutral institutions in Denmark. Membership of the organization is voluntary, but the members' products have to be controlled and comply with certain criteria in order that the companies can sustain their membership. Thus, the organization has helped in eliminating poorly manufactured roof products.

Among the requirements to comply with in order to be accepted by the organization, roof cassettes should:

- be delivered with a maximum moisture content of the plywood deck of 18% by weight (20% is accepted for the joists),
- be protected against moisture uptake during transport and delivery (i.e. be properly wrapped),
- be delivered with instructions on how the cassettes should be installed over the actual building,
- have documentation of a good moisture performance over the type of indoor climate they are designed for. Furthermore, it should be documented that excess moisture can be self-dried out of the roof before causing danger.

In practice, the last item in this list has caused leading manufacturers to use the Hygrodiode® as the preferred vapor retarder, and to use the MATCH program to document the expected performance.

Roof Inspections

A large number of unventilated cold and warm deck roofs have been inspected over the last 5 years, and the need for a strategy regarding keeping roofs dry is

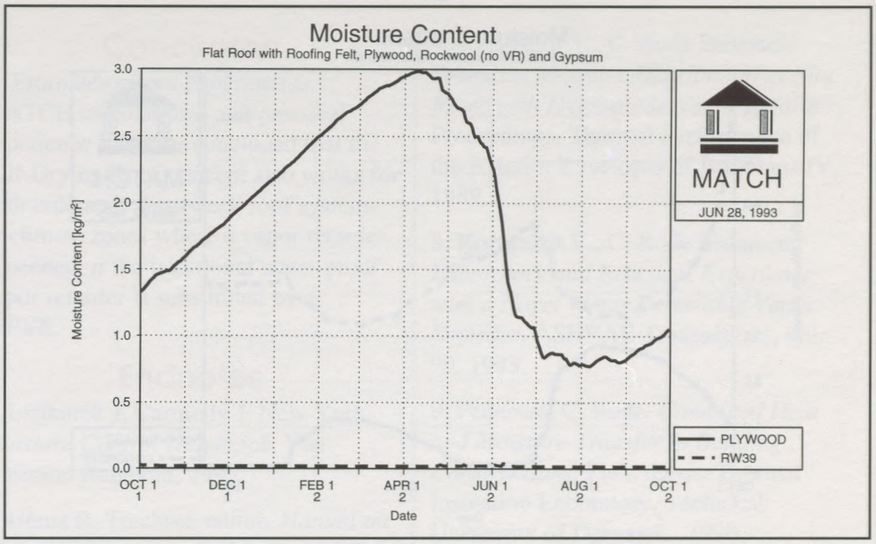

Figure 5. Calculated moisture content for the flat, cold deck roof without a vapor retarder.

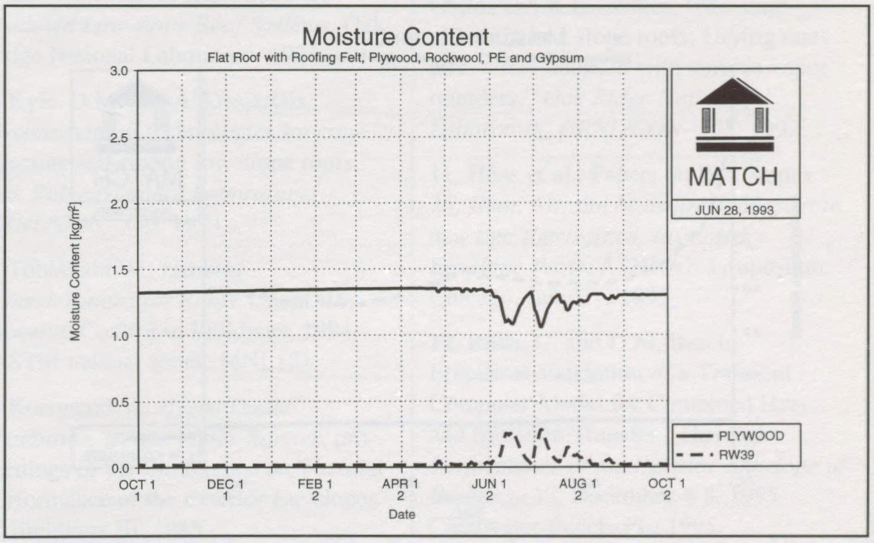

Figure 6. Calculated moisture content for the flat, cold deck roof with a polyethylene vapor retarder.

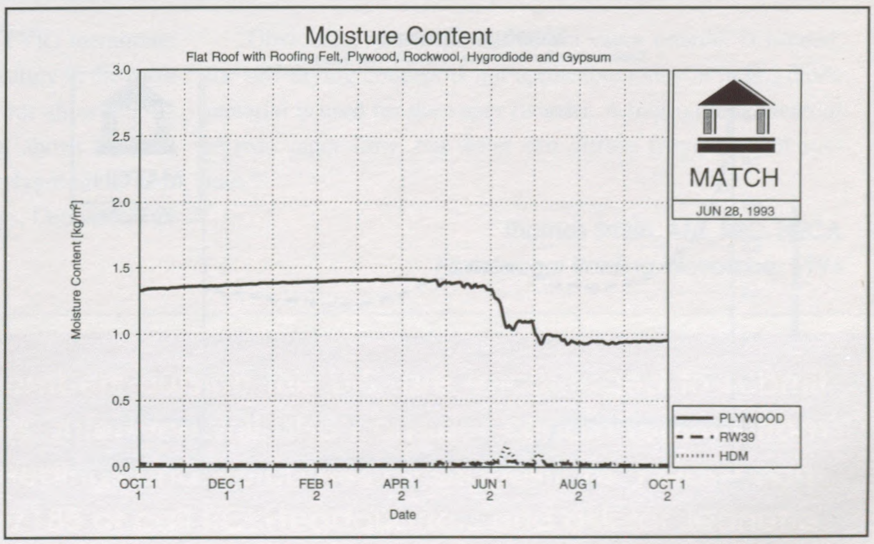

Figure 7. Calculated moisture content for the flat, cold deck with a WPVR.

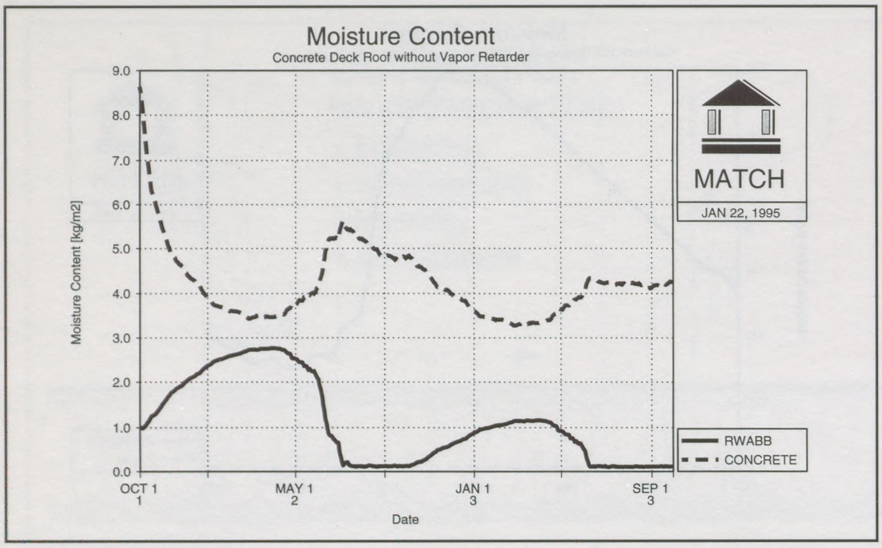

Figure 8. Calculated moisture content for the flat, warm deck without a vapor retarder.

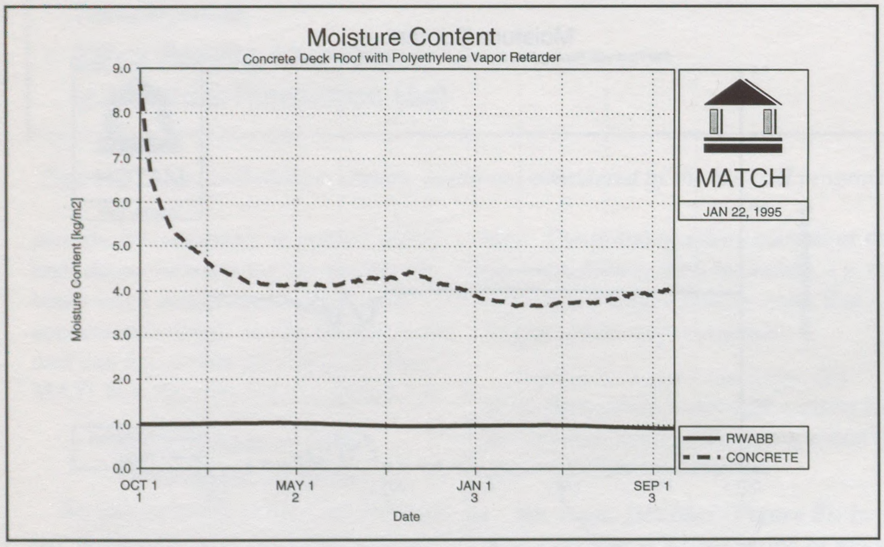

Figure 9. Calculated moisture content for the flat, warm deck with a polyethylene vapor retarder.

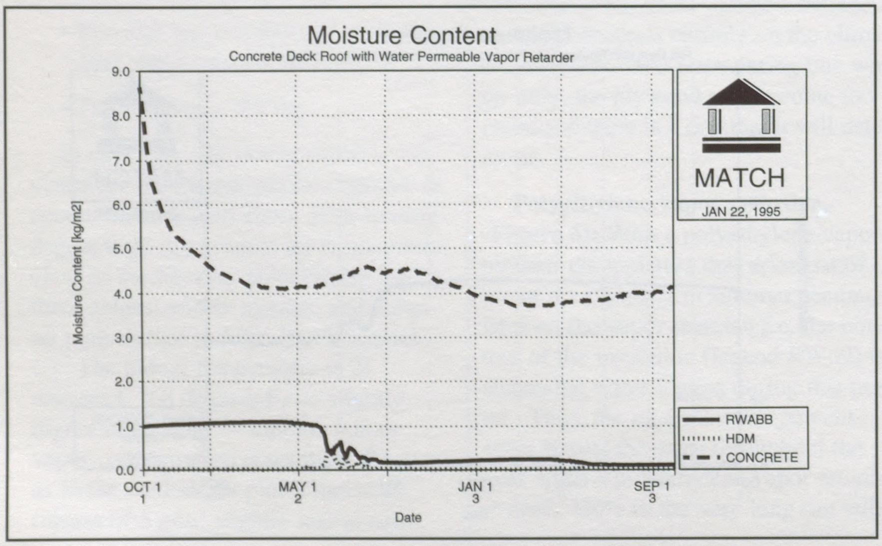

Figure 10. Calculated moisture content for the flat, warm deck with a WPVR.

clear.

Water or moisture trapped between two water and vapor tight membranes (the roof membrane and the vapor retarder of bitumen, EPDM, or PE-foil) will stay in the roof for a very long period of time.

Effective ventilation of cold deck roofs is difficult to achieve in large roofs due to the fact that roof vents penetrating the roof membrane may cause moisture transport by convection of indoor air through flaws in the vapor retarder.

In warm deck roofs, ventilation by roof vents gives the same convection risk as in the cold deck roofs. Furthermore, the resistance in the roof insulation against air flow is too large to provide the necessary air transport to dry out the warm deck roof.

The need for a self drying roof concept is obvious.

Cold Deck Roofs

In Denmark, a large number of unventilated cold roofs with wooden structure and vapor retarder of PE-foil was installed during the 1980s. Inspection of these roofs in the last 5 years has shown a number of severe rot and fungal attacks that necessitated a total renovation of the roofs.

The moisture in the unventilated roofs has two main sources:

- Water entering the roof system during installation due to bad workmanship from the installer: *construction* water.
- Water from leaks in the roof membrane during the service life of the roof.

The construction water is the major moisture problem in the cold deck roofs.

Furthermore a new problem has arisen from pumping effects in loosely laid and mechanically fastened membranes. When the wind suction lifts the membrane, moist indoor air is pumped into the roof through joints in the roof system. This problem can be avoided by sealing the joints (substrate).

Inspection of newer roofs with WPVR has shown that even built-in water will disappear in 1-2 years.

Warm Deck Roofs

Investigations of warm deck roofs have shown that the roof insulation is wet in 25- 50% of the 10-20 year old roofs. Again the two main reasons are built-in water and water from leaks in the membranes. Even in new roofs, wet roof insulation can occur.

Experience has shown that water amounts of less than 1-2 kg of water per m^2 absorbed in the insulation can be accepted. In the worst cases, amounts of as much as 40-50 kg (88-110 lbs) of water per m^2 have been observed in insulation thicknesses of 100 mm (Bathtub Syndrome).

Warm deck roofs can be scanned with a capacitance scanner. The scanner is calibrated by gravimetric sampling of the roof insulation.

It is very important to locate the wet insulation in the roof before renovating it. Especially when renovating with mechanically fastened roofing, wet insulation must be removed to avoid leak problems around the fasteners.

When using a water permeable vapor retarder, the water can be drained slowly out of the roof without causing severe problems, and a number of inspections and roof renovations have confirmed this in practice.

Conclusion

From laboratory experiments, MATCH calculations, and practical experience it can be concluded that the Self-Drying Roof concept also works for both cold and warm-deck roof systems in climate zones where a vapor retarder is needed, *if* the traditional water proof vapor retarder is substituted by a WPVR.

Endnotes

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The Water Permeable Vapor Retarder (WPVR) membrane can be regarded as a hygro-diode. It stops moisture in the form of water vapor usually coming from below, but allows moisture in the form of free water coming from above to drain through. Further information on the WPVR, Hygrodiode® can be obtained from HygroWick International Aps, Denmark, Fax (45) 42 18 07 09.

"Obviously, in situations where a vapor retarder is needed, the self-drying concept is not applicable unless a hygro-diode material is used for the vapor retarder. A hygro-diode material retards vapor flow, but water can diffuse from the roof system."

Thomas Smith, AIA, RRC, NRCA
***Professional Roofing*, November 1994**

All RCI members and nonmembers outside the U.S. are encouraged to submit technical papers and articles. *Interface* will also consider certain reprints from other publications and proceedings and welcomes all suggestions. Please contact Lyle Hogan at (910) 768-7185 or call RCI Headquarters and ask for Jeanette.