Wooden Roof Structures with High Vapor Retarder, Low Vapor Retarder, and Moisture-Dependent Vapor Retarder

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ABSTRACT

In the moderately cold climate areas, the assessment of the vapor retarder for insulated wooden roof structures is important. In the case of a tight roofing felt, it is common to use retarders with a resistance of 100 m at the inside of the structures. A condensation amount of less than 50 g/m² will arise. However, in the case of built-in moisture, the structure cannot dry out and damage will follow. With a resistance of 2 m, the amount of condensation increases to 250 g/m², but the built-in-moisture can dry out. For a pitched roof (toward the south) with an extremely high initial wooden moisture content of 30 V-% (0.3 m^3/m^3) the drying process takes about four years. With a moisture-dependent vapor retarder (wintertime 4 m, summertime 0.5 m) the moisture behavior of the insulated wooden structure can be improved further. In the case of a vapor permeable roofing membrane, the drying out process of the rafters and the roof battens can be reduced to three months without any condensation in the future. A simulation has been performed for coupled heat, air, and moisture transfer in building structures with hourly values of the Test Reference Year of Munich as boundary conditions.

INTRODUCTION

In new buildings, almost every roof room (attic space) is used today for living purposes and/or prepared for a later expansion. Today modernization is always in the foreground in addition to pure maintenance. A cause for this trend is to create floor space under the roof without buying expensive ground. The demands of the clients on the planning and the preparation of living room in the mansard can be summarized often as follows:

- attractive design
- cost-conscious realization
- definitely free of damage (while building and in future)

Mainly responsible for a long-term avoidance of building damage is competent moisture protection planning for the roof. Nevertheless, there is an often occurrence of visible moisture damage in insulation materials, rafters, or in the wooden roof boards; in addition, the heating costs increase parallel to this because the thermal insulation effect in the case of wet building materials is considerably reduced.

Today buildings are finished and covered in shorter and shorter time periods. The building envelope is made more and more dense on account of the legal orders and the available products (e.g., window). Nowadays when the tenants move into the building, the built-in moisture is much bigger than some years ago and, accordingly, this moisture must dry out in the first years after finishing.

The objective of the paper is to verify, using the simulation program DIM (now DELPHIN 4.1) for the coupled heat, moisture, and air transport in building components, that vapor retarders with a certain vapor resistance (here 2.0 m, which means the material has the same vapor resistance as an air layer with a thickness of 2 m, also called s_d value)—here called a low vapor retarder (see Figure 3)—or a moisture-dependent vapor retarder with resistances in the same area meet contemporary orders according to technical systems of rules and standards for steep roofs.

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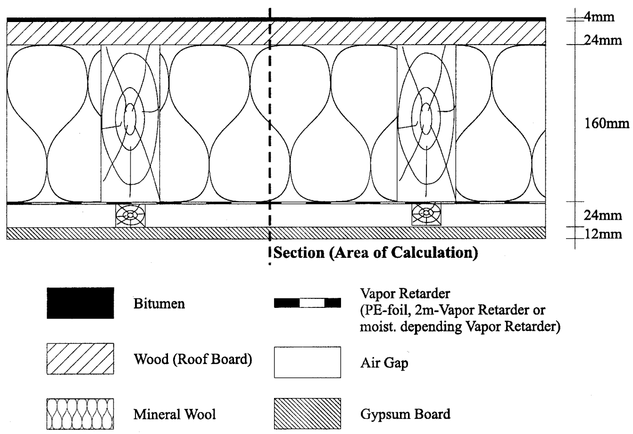

Figure 1 *Construction of the roof with a vapor retarder of bitumen over the roof boards.*

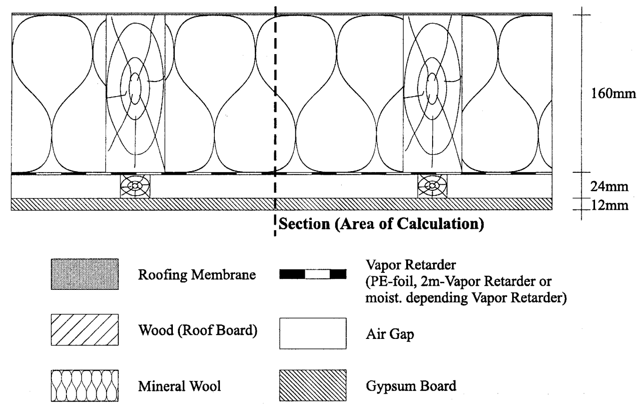

Figure 2 *Construction of the roof with a roofing membrane layer (USB) over the mineral wool insulation layer.*

In the case of crucial situations (e.g., outside bitumen layers as vapor retarder) the drying out process of timber roof constructions is positively influenced by using an inner vapor retarder with a low vapor resistance instead of a PE foil. The PE foils used today have a vapor resistance of more than 100 m and are authorized without proof according to the German standard DIN 4108-3.

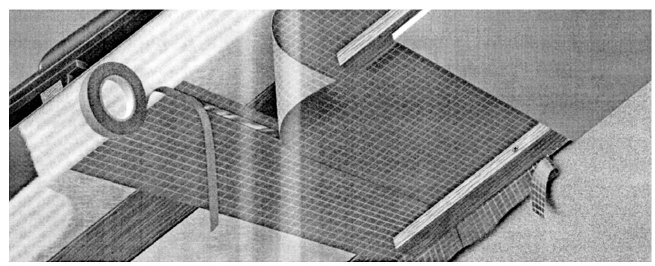

Figure 3 *Practical mounting of the low vapor retarder.*

ROOF CONSTRUCTION AND CLIMATIC LOAD

Figures 1 and 2 show schematically the construction of the two examined timber roof structures with subsequent rafter insulation. The calculations for this contribution are all one-dimensional and without air flow through the construction. The dashed line in the drawing shows the calculation area. The computer code used DIM 3.1 (now DELPHIN 4.1) also allows two-dimensional calculations and air flow in the materials (pore ventilation). A two-dimensional calculation of a roof construction with a Danish liquid permeable vapor retarder has been published in Rode (1996) and Häupl et al. (1996). A two-dimensional problem in the case of a damaged roof, solved by means of the LATENITE program, is discussed in Salonvaara et al. (2000). Häupl has an example of a calculation with air flow through a lightweight construction.

A ventilated gap with a thickness of 40 mm is above the bitumen layer and/or the roofing membrane layer in the area of the battens/counter battens. On top of this roof, tiles are installed, which are not drawn in Figures 1 and 2. The bitumen layer in Figure 1 has a vapor resistance value of 20 m, and the roofing membrane layer (also called the USB layer) in Figure 2 a value of 0.2 m and/or (if technically feasible) a value of 0.02 m. The vapor resistance values of the vapor retarder come to 180 m for the PE film, 2 m for the low vapor retarder, and between 4 m and 0.5 m for the moisture-dependent vapor retarder. The values for the moisture-dependent vapor retarder

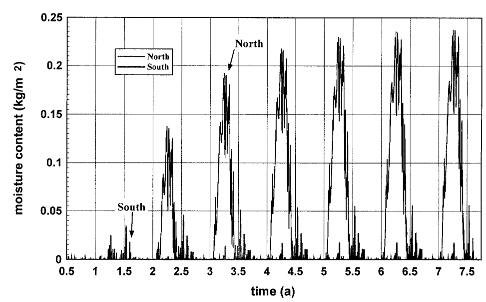

Figure 4 *Overhygroscopic moisture content over seven years in the entire roof shown in Figure 1 with bitumen and 2 m vapor retarder, roof pitch 45° to north or south, TRY Munich, without built-in moisture, beginning Oct. 1; υ = 19°C, φ = 50% to 60% RH, $a_{roof\ tiles}$ = 0.6.*

were measured at the Institute of Building Climatology. Tables 1 and 2 show the thermal and hygric material properties used. The roof constructions are to be understood as a steep roof construction with an inclination of 45° to the north and/or to the south. The practical installation of the 2 m vapor retarder is shown in Figure 3.

All cases presented are calculated with the environmental conditions of the test reference year of Munich (hourly values

TABLE 1
Simplified Material Properties

Moisture Storage Function:	$w = w_h\left(1 - \sqrt{\frac{\varphi_h - \varphi}{\phi_h}}\right) \qquad 0 < \varphi \le \varphi_h$ $w = w_s - \frac{(w_s - w_h)}{(1-\varphi_h)}(1-\varphi) \qquad \varphi_h < \varphi \le 1$
Liquid Water Transport Function (Moisture Content W As Potential):	$a_w(w) = a_{ws}\left[(k+1)\left(\frac{w-w_h}{w_s-w_h}\right)^{\frac{1}{k}} - k\cdot\left(\frac{w-w_h}{w_s-w_h}\right)^{\frac{2}{k}}\right] \qquad \varphi_h < \varphi \le 1$
Water Vapor Transport Function (Vapor Pressure P As Potential)	$\delta = \frac{1.8\cdot 10^{-10}[s]}{\mu}\left[\frac{1-w/w_s}{0.8(1-w/w_s)^2+0.2}\right] \qquad 0 < \varphi \le 1$
Thermal Conductivity:	$\lambda = \lambda_0 + \lambda_1 \cdot w$

TABLE 2 Material Properties

Material	ρ	c	λ_0	λ_1	w_h	w_s	φ_h	a_{ws}	k	μ
	kg/m³	kg/m²K	W/mK	W/mK	m³/m³	m³/m³	%	m²/s	-	-
Wood	450.0	2500	0.130	0.90	0.1000	0.6000	98	$5.0\cdot 10^{-9}$	2.0	40
USB (roofing membrane)	1000.0	1000	0.200	-	0.0001	0.0010	98	0	-	10
Bitumen	1200.0	2000	0.150	-	0.0001	0.0025	98	0	-	10000
Mineral wool	30.0	840	0.040	0.60	0.0020	0.9000	98	0	-	1
PE-foil	1200.0	2000	0.200	-	0.0001	0.0010	98	0	-	90000
2 m vapor retarder	1000.0	1000	0.2	-	0.0001	0.0010	98	0	-	1000
Air	1.3	1000	0.14	0.42	-	-	-	0	-	0.17
Gypsum board	1000.0	1000	0.340	1.10	0.0050	0.4000	98	$2.0\cdot 10^{-7}$	0.5	17

ρ =density
c =heat capacity
λ_0 =thermal conductivity of the dry material
λ_1 =parameter for the moisture dependence of the thermal conductivity
w_h=maximum hygroscopic moisture content (equilibrium to φ_h)
w_s = saturation moisture content
φ_h = hygroscopic relative humidity
a_{ws} = capillary moisture diffusivity
k = parameter for the capillary moisture diffusivity
μ = vapor resistance factor

for temperature, air relative humidity, short-wave radiation, long-wave radiation exchange, wind, and precipitation). The room climate varies periodically between 19°C, 50% RH in the winter (January 31) and 22°C, 60% RH in the summer (August 1). Moreover, measured values for the inside and outside boundary conditions can also be used Häupl et al. (1999). The hygrothermal conditions in the air gap were modeled separately for this contribution. The temperature in the air gap is calculated by using a simple analytical flow model with the outside and inside air temperature, the solar radiation on the roof tiles, the dimensions of the air gap, and the thermal properties of the materials used as parameters. The relative humidity results from the values of the Munich test reference year. The absorption coefficient of the roof tiles for short-wave radiation is $a_{roof\,tiles} = 0.6$. This model has not been published yet.

RESULTS

Timber Roof Construction with Mineral Wool Insulation and Bitumen Sealing

For the roof construction shown in Figure 1, with a bitumen layer and a low vapor retarder and without bigger built-in moisture (rafter and roof boards are nearly dry, which means in balance with 80% relative humidity), results after approximately seven years include a condensation amount of 240 g/m² in wintertime at a northern roof and 45 g/m² at a southern roof in the built-up state (Figure 4 and Table 3). Distributed on the roof boards, these correspond to an increase of the moisture content in the wood to 2.5 and/or 0.5 mass percent. The claims of the German DIN 4108, page 3, $w_T < 0.5$ kg/m² (condensation mass in 60 days in winter climate) and $\Delta u_{m,wood} < 3$ mass percent are fulfilled. Of course, easy analytical methods (such

TABLE 3
Maximum Overhygroscopic Moisture Content (Condensate) for the Construction

	North		South	
	October 1	**May 1**	**October 1**	**May 1**
Bitumen/2 m vapor retarder	238 g/m²	236 g/m²	46 g/m²	45 g/m²
Bitumen/PE film	12 g/m²	12 g/m²	*22 g/m²	*21 g/m²
Bitumen/moist-dependent vapor retarder	5 g/m²	4 g/m²	*9 g/m²	1 g/m²

* Raised values by summer condensation.

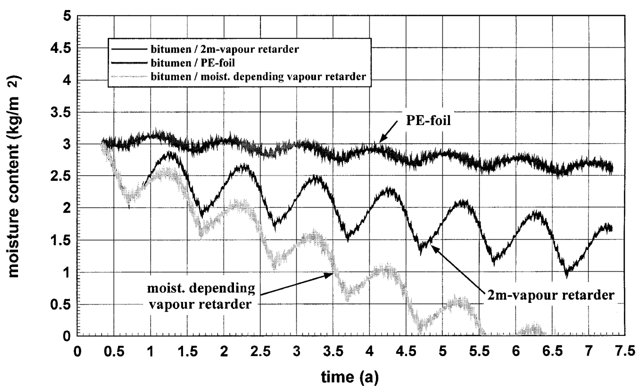

Figure 5 *Overhygroscopic moisture content over seven years in the entire roof shown in Figure 1. Roof pitch 45º to the north, TRY Munich, with built-in moisture, beginning May 1;* υ *= 19ºC to 22ºC,* φ *= 50% to 60% RH,* $a_{\text{roof tiles}}$ *= 0.6.*

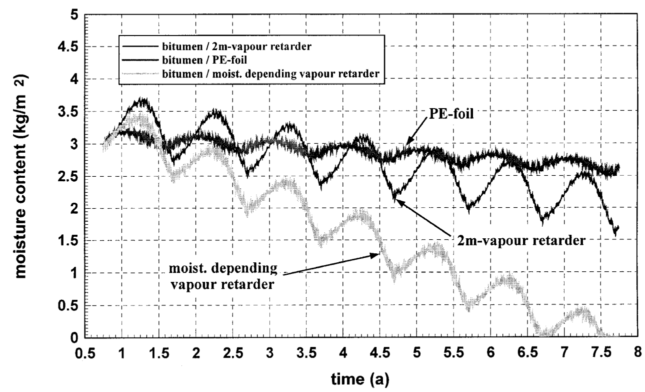

Figure 6 *Overhygroscopic moisture content over seven years in the entire roof shown in Figure 1. Roof pitch 45º to the north,TRY Munich, with built-in moisture, beginning October 1;* υ *= 19ºC to 22ºC,* φ *= 50% to 60% RH,* $a_{\text{roof tiles}}$ *= 0.6.*

as the GLASER scheme in the DIN 4108) are limited, suitable to quantify the hygrothermal behavior of roof constructions. An improvement of the easy vapor diffusion model by the inclusion of capillary conductivity and moisture retention characteristics, as well as its validation and limits of use, have been published in Häupl et al. (2001).

Of course, by using a PE foil, the condensation amount is less. However, the disadvantage of the vapor retarder becomes visible in the case of built-in moisture.

The roof construction shown in Figure 1 with built-in moisture clearly shows the advantage of the 2 m vapor retarder compared to the PE foil (Figures 5 to 8). The built-in moisture is simulated by using an initial moisture content of the rafter and the roof board of 3.0 kg/m² resp. 25 M% (0.25kg/kg or 0.11m³/m³) in the wood. In order to use the drying potential of the first summer, the roof should be finished in the spring. A northern roof nevertheless dries back from 3.0 kg/m² onto 1.0 kg/m² in seven years (Figure 5). For a southern roof, even a total drying out (Figures 7 and 8) occurs. However, the inner sealing with a PE foil almost completely prevents drying out (Figures 5 to 8). Künzel and Sedelbauer demonstrate similar results (Künzel 1998; Sedelbauer and Künzel 2000).

In Figure 9 the moisture field for the roof in Figure 1 is represented (bitumen layer, 2 m vapor retarder, and built-in moisture) for the second year and the beginning of the third year after simulation beginning on May 1. The maximum moisture in the wintertime in the roof boards decreases due to the drying potential of the second to the third winter period. During the summer, condensation occurs on the vapor retarder by reversal diffusion. The amount of this condensation decreases in the course of the years.

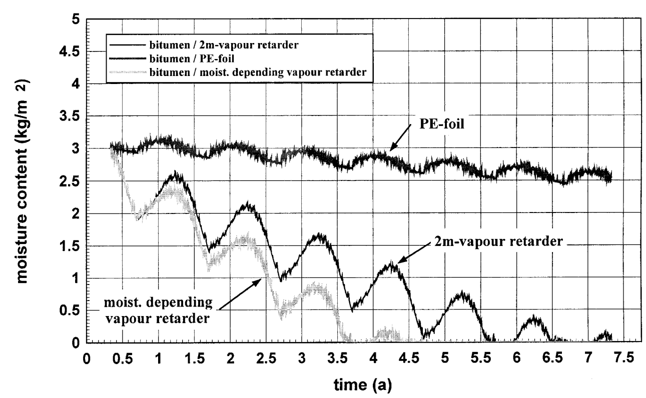

Figure 7 *Overhygroscopic moisture content over seven years in the entire roof shown in Figure 1. Roof pitch 45º to the north, TRY Munich, with built-in moisture, beginning May 1;* υ_i *= 19ºC to 22ºC,* φ_i *= 50% to 60% RH,* $a_{\text{roof tiles}}$ *= 0.6.*

The U-factor of the roof construction is between 0.21 W/m²K (no built-in moisture) and 0.24 W/m²K (built-in

TABLE 4
Maximum Overhygroscopic Moisture Content (Condensate) for the Construction Shown in Figure 2

	North		South	
	October 1	May 1	October 1	May 1
USB (0.02 m)/2 m retarder	6 g/m²	6 g/m²	2 g/m²	2 g/m²
USB (0.02 m)/PE foil	0 g/m²	0 g/m²	2 g/m²	2 g/m²
USB (0.2 m)/2 m retarder	41 g/m²	41 g/m²	38 g/m²	38 g/m²
USB (0.2 m)/moisture-dependent vapor retarder	26 g/m²	26 g/m²	23 g/m²	23 g/m²
USB (0.2 m)/PE foil	11 g/m²	11 g/m²	7 g/m²	7 g/m²

TABLE 5
Drying Time for the Roof Construction Shown in Figure 2

	North		South	
	October 1	May 1	October 1	May 1
USB (0.02 m)/2 m retarder	130 d	62 d	129 d	63 d*
USB (0.02 m)/PE foil	114 d	70 d	113 d	72 d*
USB (0.2 m)/2 m retarder	256 d	97 d	250 d	97 d*
USB (0.2 m)/moisture-dependent vapor retarder	246 d	98 d	237 d	97 d*
USB (0.2 m)/PE foil	241 d	123 d	233 d	130 d*

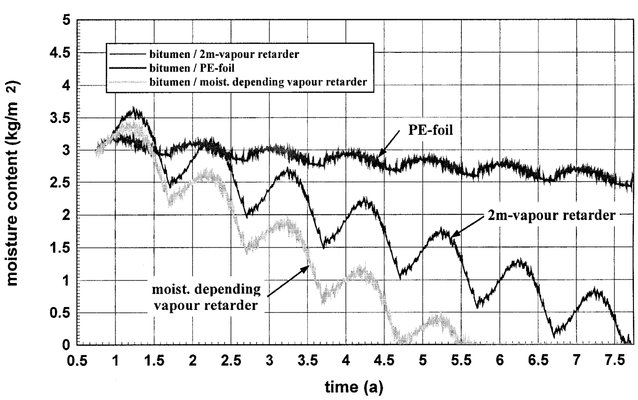

Figure 8 *Overhygroscopic moisture content over seven years in the entire roof shown in Figure 1. Roof pitch 45º to the north or south,TRY Munich, with built-in moisture, beginning October 1;* υ_i = *19ºC to 22ºC,* φ_i = *50% to 60% RH,* $a_{\text{roof tiles}}$ = *0.6.*

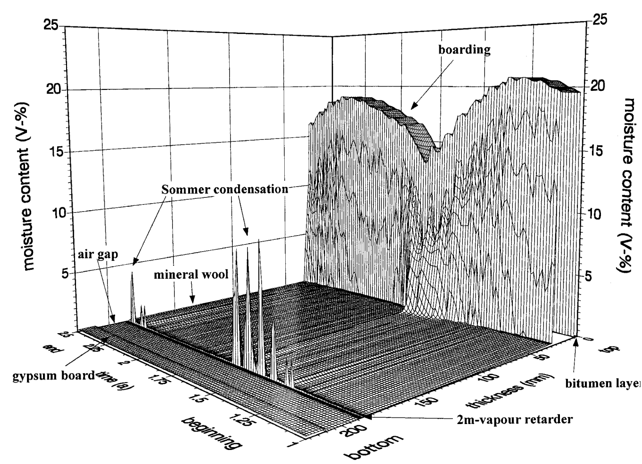

Figure 9 *Moisture distribution in the roof construction with bitumen layer and 2 m vapor retarder in the second year; roof pitch 45º to the south, TRY Munich, with built-in moisture. Beginning of the simulation is May (compare Figure 7), figure dated from January 1, second year, to June 30, third year.*

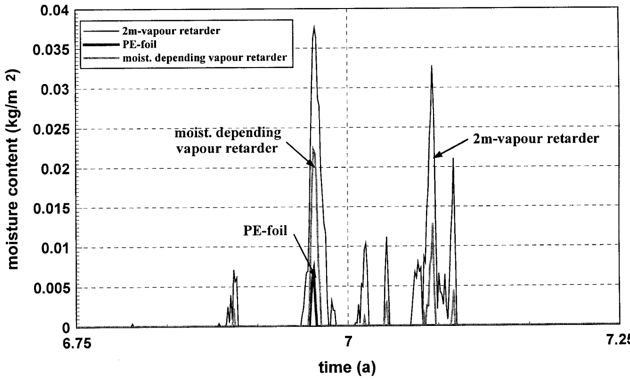

Figure 10 *Overhygroscopic moisture in the entire roof shown in Figure 2 in the seventh winter (October 1 to April 2), roof pitch 45° to the south, TRY Munich, without greater built-in moisture, beginning October 1.* $\vartheta_i = 19°C$ to $22°C$, $\varphi_i = 50\%$ to 60% RH, $a_{\text{roof tiles}} = 0.6$.

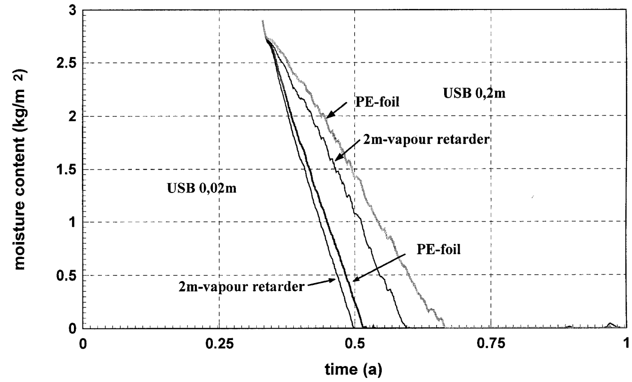

Figure 11 *Decrease of the overhygroscopic moisture in the entire roof construction shown in Figure 2 for the variants with roofing membrane layer (USB) in the first year, roof pitch to the north side, TRY Munich, with built-in moisture, beginning May 1.* $\vartheta_i = 19°C$ to $22°C$, $\varphi_i = 50\%$ to 60% RH, $a_{\text{roof tiles}} = 0.6$.

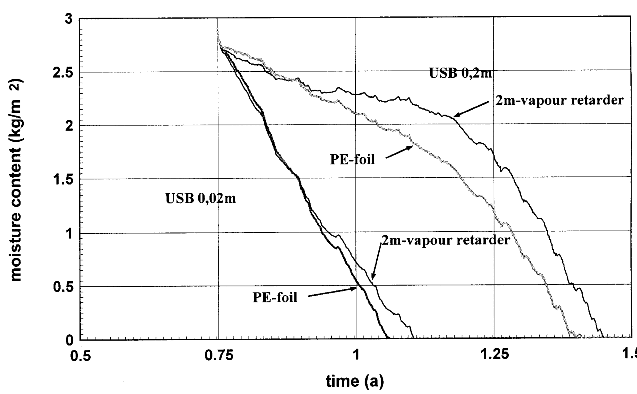

Figure 12 *Decrease of the overhygroscopic moisture in the entire roof construction shown in Figure 2 for the variants with roofing membrane layer in the first year, roof pitch to the north side, TRY Munich, with built-in moisture, beginning October 1,* $\vartheta_i = 19°C$ to $22°C$, $\varphi_i = 50\%$ to 60% RH, $a_{\text{roof tiles}} = 0.6$.

moisture). These values contain the gains through radiation (reduced by the ventilated roof) and the losses due to moisture content and moisture transport. The difference is so small because the liquid moisture in rock wool is only in a very small area near the roof boards (winter) or near the vapor retarder (summer). In the rest of the mineral wool layer, the moisture distribution is uniform.

Wooden Structure with Roofing Membrane Layer Over the Mineral Wool Insulation

For the roof construction shown in Figure 2 without greater built-in moisture (rafter and mineral wool in balance with relative humidity of 80% RH) the situation is completely uncritical because of the relatively high vapor permeability of the roofing membrane. For a vapor resistance value of 0.2 m in connection with the 2 m retarder, the condensation amount reaches 40 g/m^2 for (theoretically) 0.02 m, even 10 g/m^2 (Figure 10 and Table 4).

In case 2, the high built-in moisture of 3.0 kg/m^2 is now distributed over the rafters and into the insulation layer. With a vapor-permeable roofing membrane layer, the built-in moisture dries out faster in the first summer with the 2 m vapor retarder (a maximum of three months) than with the PE foil (a maximum of four months); see Table 3 and Figure 11. With the installation in October, a small amount of condensation results in the first winter (see Table 5 and Figure 12); in the second summer, the roof also dries out. The U-factors vary between 0.21 and 0.24 W/m^{2}K.

SUMMARY AND CONCLUSIONS

Insulated wooden roof constructions with a bitumen layer should be equipped internally only with a mild vapor retarder —s_d value of some meters—or with a moisture-dependent vapor retarder with the same value and not with a vapor-tight PE foil (s_d > 100 m). In this case the initial built-in moisture dries out in the course of the years, and the annual winter condensate is less than 0.3 kg/m^2, which fulfills the German norm DIN4108 for sensitive materials.

Insulated wooden roof constructions with a diffusion open roofing membrane layer ($s_d \leq 0.2$ m) dry out in the first summer if finished in May or in the next one if finished in October. The winter condensate amount is less than 50 g/m^2 and almost independent of the kind of the vapor retarder.

The validity of the simulations with the program DIM has been confirmed through comparisons of measurements and calculations on test houses (Häupl et al. 1999; Fechner et al. 1998).

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