Impact of Cool Roofing Membranes on the Hygrothermal Performance of Low-Sloped Roof Structures in Timber Construction

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ABSTRACT

This paper will present an analysis regarding the hygrothermal performance and furthermore durability of non-ventilated light-weight flat roofs with cool roofing membranes in the Central European climate.

The main focus is the assessment of the drying potential of selected roof variants to predict the potential risks of mold and especially wood decay fungi growth inside the constructions. Several numerical simulations were carried out to investigate the influence of different roofing membranes and especially cool roofing products on the overall hygrothermal conditions inside the constructions.

Additionally, roof assemblies with cool roofing membranes were investigated at the Austrian BSRTU Building Science – Research & Test Unit outdoor test facility (www.building-science.at) of the Carinthia University of Applied Sciences (CUAS). In-situ measurement results, taken at this experimental set-up will be discussed.

INTRODUCTION

This paper presents first results of a research project on the durability of non-ventilated, highly-insulated timber-framed low-sloped roofs in the climate of Central Europe. The primary aim of the work was to investigate the influence of different colored roof membranes on their hygrothermal response. The calculations were performed for light-grey, dark-grey, and especially white colored (cool roofing) membranes, basically looking to their drying potential due to solar-driven diffusion. It is important to note, that usually in Austria, according to code OENORM B8110-2, avoiding interstitial condensation is evaluated using the dew-point method (Glaser scheme). However, the method as applied in the code, only considers very simplified steady-state boundary conditions. Neither solar radiation and undercooling, nor wetting processes and hygroscopic sorption, nor liquid transport are taken into account. Therefore, the scope of this study is to predict the long-term durability as realistically as possible using transient hygrothermal calculations.

INVESTIGATED CASES

In the frame of the research, the drying potential of prefabricated timber low-sloped roof constructions, which are used more and more for larger commercial and production, but also residential buildings in Austria, was analyzed. These roofs are typically prefabricated and consist of 400 mm (16 in.) high timber beams faced with OSB decking at both sides. The space in between the beams is filled with blown-in cellulose insulation. Based on this base case, three variants with different colored waterproofing membranes were analyzed (Table 1 and Figure 2). All analyses assumed the roof structures cases 1 to 3 to be airtight and the insulation correctly installed, so no convective vapor flow could develop, affecting moisture buildup.

SIMULATIONS

The simulations were carried out with the WUFI® (Wärme und Feuchte instationär [Transient Heat and Moisture]) software, developed at the Fraunhofer Institute for Building Physics (Kuenzel 1994) in Holzkirchen/Germany and validated against outdoor measurements and laboratory tests.

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The analysis was conducted under the assumption that the roof structures had good airtightness and insulation installation, and thus without convective vapor flow affecting moisture buildup.

Default Program Settings

The surface film coefficient at the inside surface was set equal to 8 W/($m^2 \cdot K$). Exterior climate data and surface temperatures, measured at three roof sections with different colored membranes (white, light grey, dark grey) at the Building Science Research & Test Unit (BSRTU) outdoor test facility were chosen as exterior boundary conditions.

The room climate varied as a sine curve between 20°C and 40% relative humidity in winter and 22°C and 60% relative humidity in summer. As initial conditions for the materials 20°C and an RH of 80% were chosen (Karagiozis 1998). Such high moisture content (i.e., 80%) may be due to rain during transport and mounting of large roofs structures or even due to flank diffusion over adjacent masonry (Kuenzel 1996).

The material parameters required for each material were taken from respective product spec sheets, approved due to third party laboratory report (Table 2). The hygrothermal behaviour was simulated over a period of five years, starting on October 1st.

RESULTS

The results concern the hygric behaviour of the assemblies. Moisture tolerance, in fact, is a critical performance in building envelope design. Hence, for analyzing the drying potential, total water content in the whole construction was calculated. Further, the water content in the different layers and especially the timber based ones was analyzed to assess the possibility of wood decay. According to Austrian codes the critical limit for the moisture ratio in timber is 20 mass percent (M%) although it is well known that wood detoriation mainly occurs at higher levels and long exposure time. In addition, the relative humidity and temperatures in the interfaces between cellulose and the exterior OSB decking and the interior vapor retarder was calculated to assess the risk of mold growth based on the exposure time. In the graphs, results for the whole period of five years are shown.

Total Water Content (TWC)

First, simulations were carried out to investigate total water content for case 1, 2, and 3. Figure 2 shows the results (TWC) for the five year period. All cases show a decreasing TWC. Anyhow, the white colored cool roofing membrane applied in case 1 has the most significant influence on remaining moisture in the roof. Total water content (TWC) in case 1 with cool roofing membrane, levels off at a seasonal maximum of ~3,8 kg/m^2 after about 5 years. Case 2, with a light-

Table 1. Cases (Layers from Outside to Inside)

Case 1	Case 2	Case 3
Roof Membrane; Type: Plastic (Polyolefin); Permeance = 0.1426 perm; (s_d – Value = 23 m)		
Color: white (cool roofing)	Color: light grey	Color: dark grey
Solar Reflectance: ~ 0,78 (*)	Solar Reflectance: ~ 0,65 (*)	Solar Reflectance: ~ 0,50 (*)
Oriented Strand Board (OSB) 15 mm (5/8 in.)		
Cellulose Blown-in Insulation 400 mm (~16 in.)		
Code approved Vapor Retarder, Permeance = 0.0252 perm (s_d – Value = 130 m) (**)		
Oriented Strand Board (OSB) 15 mm (5/8 in.)		

* Solar reflectance measured according to ASTM E903: Material data from used products (spec sheet) were inserted in simulation. Note, that these values are representing initial conditions, ignoring weathering effects. The influence of soiling (decrease of solar reflectance) during the course of the years is part of the research work at the CUAS outdoor test facility.
** Vapor retarder with permanent s_d value. No smart vapor retarder with variable s_d value.

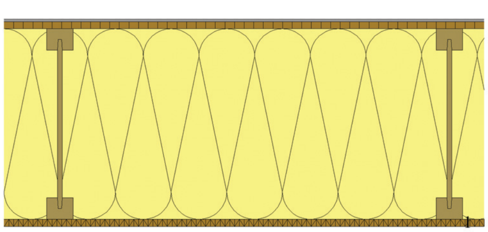

Figure 1 Schematic draft of investigated roof assemblies, cases 1 to 3.

Table 2. Material Properties

Material	Bulk Density, kg/m^3	Porosity, m^3/m^3	Heat Capacity, kJ/kg·K	Heat Conductivity Dry, W/m·K	Diffusion Resistance Factor Dry μ [–]
Oriented strand board (OSB)	615	0,6	1880	0,101	∅ 175
Cellulose	50	0,95	2000	0,038	1,8

* Material data taken from respective product spec sheets, approved by third party laboratory report.

grey membrane is showing an improved and even faster drying. The total water content levels off at a seasonal maximum of ~ 3,6 kg/m^2. Case 3 with the dark-grey colored waterproofing membrane shows the fastest drying rate of all variants. Higher temperatures at the exterior surface, due to a higher short wave absorptivity of the membrane, in fact increase the inwards vapor pressure gradient accelerating drying that way. The total water content levels off at a seasonal maximum of ~ 3,55 kg/m^2 after five years.

Clearly inward drying capacity should be considered as an important design factor. (Powell and Robinson, 1971; Straube, 2001; Desjarlais, 1995)

Water Content (WC) Exterior OSB Decking

The next step in this parametric study was to predict the moisture response of the wooden components and especially the exterior OSB decking. In Figure 3 one can observe that the moisture content of the OSB for all cases is exceeding 20 M% during the first wintertime and then decreasing over the years. In cases 2 and 3, the water content decreases faster during the first five years and levels off at about ~135 kg/m^3 (Case 2) and ~ 120 kg/m^3 (Case 3), respectively, during the winter time in the fifth year and therefore below or rather slightly above the critical limit of 20 M%.

Only the moisture content of the exterior OSB in case 1 with the white colored cool roofing membrane remains at a higher humidity level during all five winter periods increasing beyond 20 M%. This effect is quite crucial for the practical application since the unscheduled moisture within the construction will be trapped inside the roof construction for a longer time due to poor solar-driven diffusion. This potential higher humidity level during long periods would promote the risk of mold or even decay fungi growth and hence a potential premature construction failure.

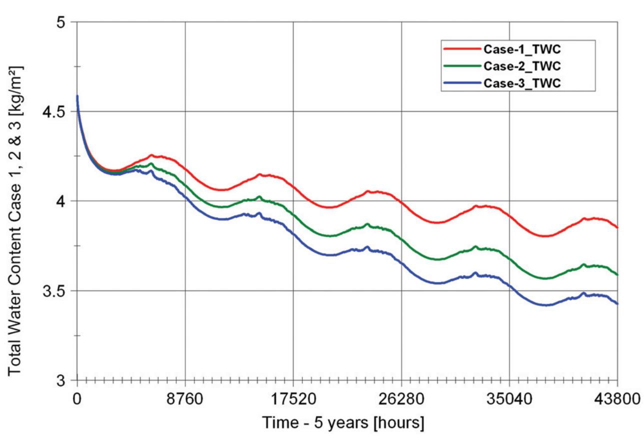

Figure 2 *Calculated total water content (TWC) of cases 1, 2, and 3.*

Relative Humidity on the Interface to Cellulose

In addition, the relative humidity on the interface between external OSB decking and the cellulose insulation was calculated to assess the risk of mold growth (Figure 4). The simulations were started with an initial moisture content of 80% rh. This higher moisture content at the start is useful to predict the construction's drying. The simulation is predicting a higher RH of ~95% during the first winter for all constructions due to the higher initial moisture conditions. In principle, mold growth is possible at RH of >80% and >5°C. In Figure 4 it is also well to see, that case 2 with a light-grey colored membrane and case 3 with a dark-colored membrane are showing the best drying. The RH at the interface external OSB cellulose is therefore continuously decreasing during the time of investigation and remains below the critical border of 95% rh after the fifth year. In addition, in case 1 with the cool roofing membrane the RH remains above 95% rh every wintertime.

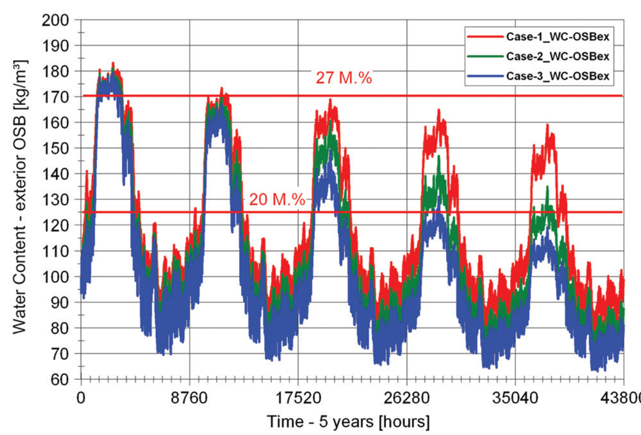

Figure 3 *Calculated moisture content (by mass) of the external OSB, cases 1, 2, and 3.*

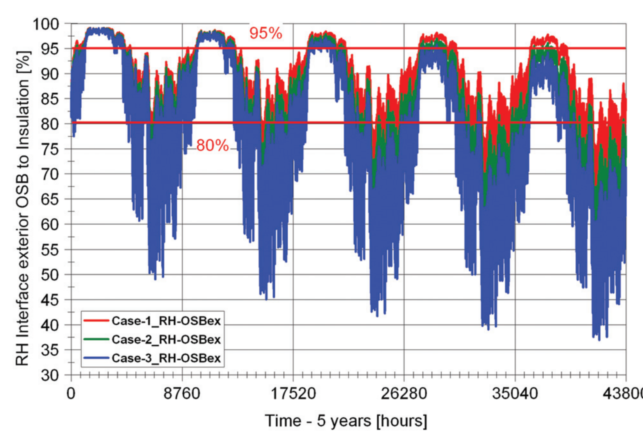

Figure 4 *Relative humidity at the external OSB-cellulose interface, cases 1, 2, and 3.*

Cases 2 and 3 are showing a decreasing gradient, but nevertheless 80% rh are exceeded during some weeks within wintertime when the temperatures (Figure 6) are reduced. It has to be noted that blown-in cellulose is blended with fungicides like boric acid, boric pentahydrate, etc. by default. In cases of a direct contact between wooden surfaces and cellulose, these additives should limit the germination of mold growth under moisture conditions between 80% and 90%. The effectiveness of the above mentioned fungicidal additives in wooden constructions has been investigated in a laboratory test at the Carinthia University of Applied Sciences and in-situ measurement results from practice confirm this theory. Due to the lower temperatures during this time of the year and the fungicidal influence of cellulose, mold germination should be reduced or even limited, if cases 2 and 3 are executed with dry materials.

Furthermore, the calculation of the relative humidity at the interface between the OSB board and the cellulose in case 1 with the cool roofing membrane indicates a potential risk of mold growth during the whole period of investigation. Figure 4 illustrates that the RH is exceeding 80 % for several months during the first five years with a seasonal maximum of 90% to 95% rh. Mold growth is therefore likely to occur.

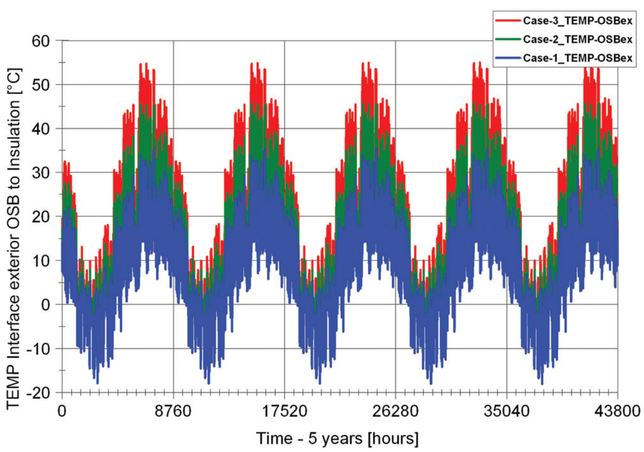

Figure 5 *Temperature at the external OSB-celluose interface, cases 1, 2 and 3.*

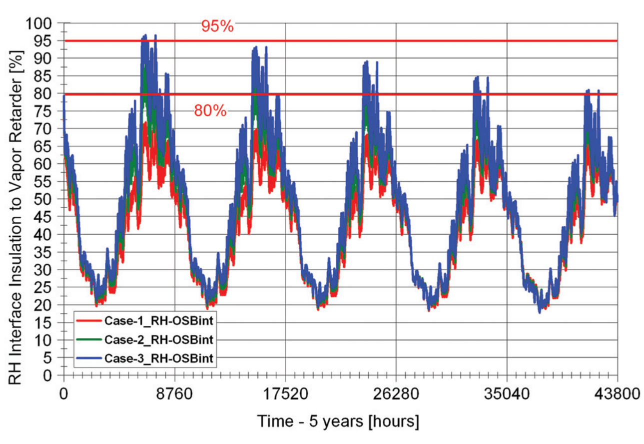

Figure 6 *Relative humidity at the internal vapor retarder-cellulose interface, cases 1, 2 and 3.*

Provided that good workmanship was done, only the roof constructions case 2 and 3 are showing a relatively good hygric behavior. Under these circumstances moisture related problems like mold and wood decay fungi growth at the exterior OSB boards should be avoided in these cases.

In a second step, the relative humidity at the interface between cellulose and the interior vapor retarder was calculated. It is well to see that in variants 2 and 3 the RH at the interface between cellulose and internal vapor retarder is generally exceeding 80% rh during the first and second summer due to the assumed higher initial moisture conditions (Figure 6). The higher short wave absorptivity of the light-grey and dark-grey colored membranes is improving the solar driven inwards diffusion, and hence a higher RH at the interface of the vapor retarder foil and the cellulose is occurring. Case 1 with the cool roofing membrane is showing a continuously decreased gradient and is remaining below 80% rh without the risk of mold germination, because the lower surface temperatures are reducing inward diffusion drying.

IN-SITU MEASUREMENTS AT BSRTU OUTDOOR TEST FACILITY

In 2010, several low sloped roof construction test assemblies were installed at the CUAS outdoor test facility, built in South Austria. One part of the roof section was used to investigate the hygrothermal performance of selected roof systems executed with different waterproofing membranes. For the roof assemblies a construction system similar to the previous calculated cases 1, 2, and 3 respectively, with OSB deckings on both sides of the timber I-beams and vapor retarder foils was chosen. All roof components are equipped with special measurement systems. The measurements started on December 30, 2010 and are still ongoing. The weather data is recorded using two separate weather stations and also the indoor conditions are monitored continuously. The slope of the investigated roof sections is 2° northwards.

Results—In-Situ Measurements

In this section measured results for the period of January 2011 to January 2012 are presented. On the interfaces between the external OSB decking and the internal vapor retarder foil to the cellulose insulation layer capacitive humidity and temperature sensors were installed to measure the hourly values for relative humidity and temperature (Figure 10). On the internal and external roof surfaces additional temperature sensors were applied and the climate data in- and outside the building was monitored continuously. In addition, optical radiation sensors were installed to verify the climate data which were used during the previous simulations.

Figures 11 and 12 are providing an overview about the measured data concerning outside climate and the solar radiation on the roof constructions.

The measured relative humidity and temperature (°C) values within the roof constructions are presented in Figures 13, 14, and 15.

In case 1 with the cool roofing membrane the RH at the interface external OSB and cellulose is varying between

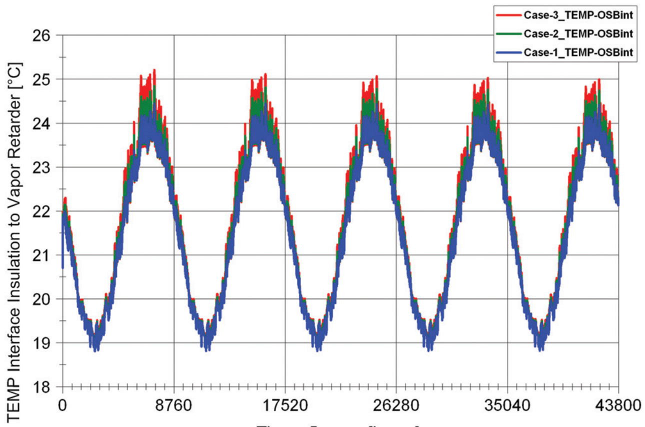

Figure 7 Temperature at the internal vapor retarder-cellulose interface, cases 1, 2, and 3.

Figure 8 In-situ measurements at BSRTU Outdoor Test Facility.

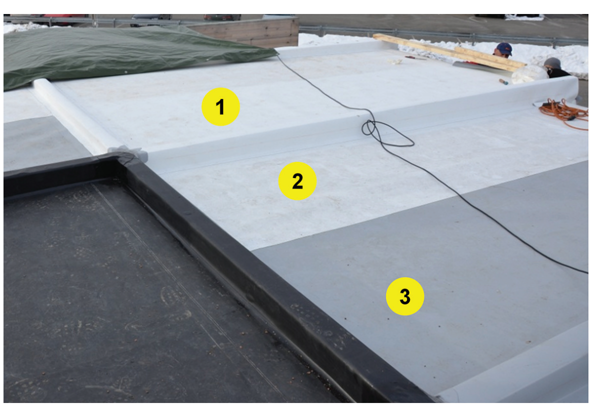

Figure 9 Test assemblies for in-situ measurements.

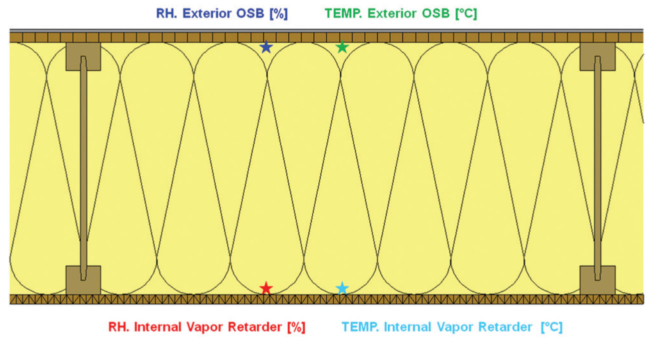

Figure 10 Positioning of sensors in test assemblies.

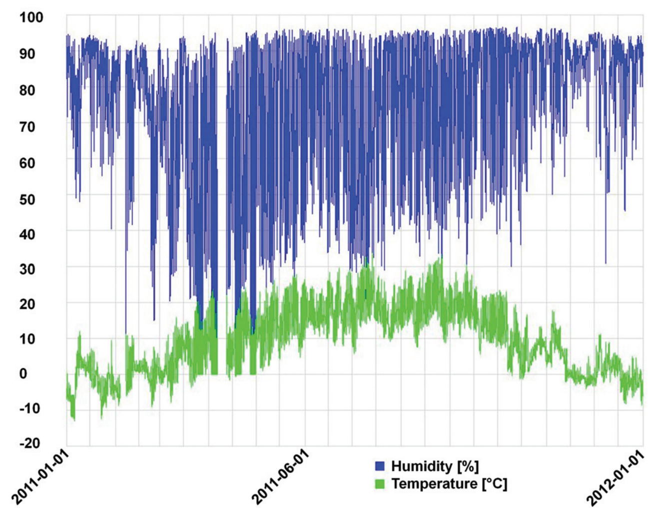

Figure 11 Measured exterior climate (relative humidity, temperature).

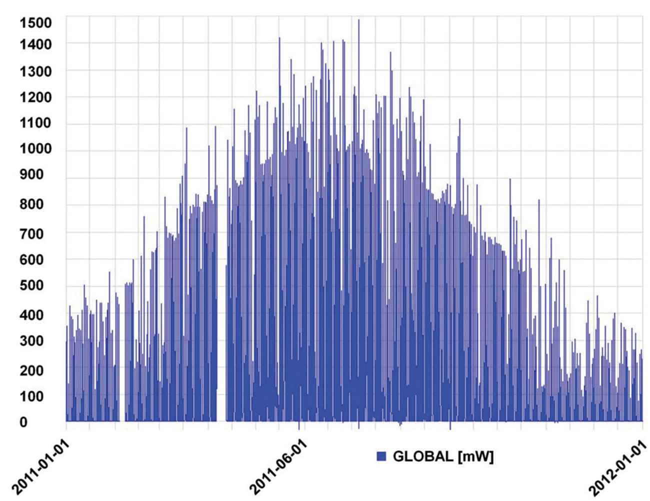

Figure 12 Measured solar radiation on roof surfaces.

~62% rh in summer and ~100% rh during wintertime (Figure 13). It is also well to see, that the RH is oscillating at a higher rate between ~70% and ~ 80% rh during the period from spring to fall. Due to the higher temperatures during this time, a certain risk of mold growth cannot be disregarded, but until now no distinctive mold or wood decay fungi growth was detected during probing. Nevertheless it's important to note that a higher water content of the exterior insulation was detected. Hence it's necessary to wait, to see how the future moisture development will proceed.

In addition, the RH at the interface between cellulose and internal vapor retarder is increasing up to ~75% RH in summer and up to ~30% RH in winter. Due to the white

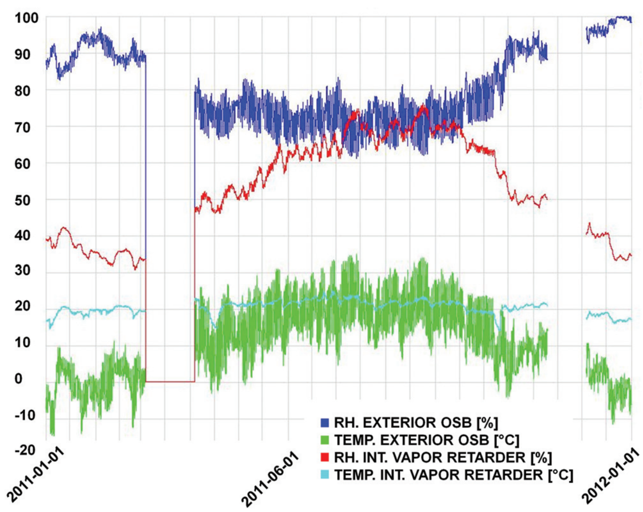

Figure 13 *Relative humidity and temperatures in test assembly 1 with white roofing membrane.*

roofing membrane lower surface temperatures are generated and hence a reduced solar-driven inward diffusions is occurring.

Figure 14 is presenting the relative humidity and temperature values within case 2, executed with a light-grey colored roofing membrane.

The RH value below the exterior OSB decking is leveling between ~50% rh in summer up to ~95% rh during a few days in winter. Although the critical limit for mold germination, 80% rh, was exceeded, no mold or wood decay fungi growth was detected during inspections until now. That's reasonable because temperatures at this time are quite low and it is assumed that the fungicidal additives in the cellulose are reducing the possibility of fungi germination on wooden surfaces, provided that a proper contact between cellulose and timber is given.

According to that, also the relative humidity on the interface between cellulose and the internal vapor retarder was measured. The RH is leveling between ~25% rh in winter and ~78% rh during summertime. The higher RH gradient is founded in the higher solar driven diffusion due to the darker membrane surface. Nevertheless, the critical limit of 80% rh is not exceeded, hence mold related problems are to be neglected.

Figure 15 is presenting the relative humidity and temperature values within case 3, executed with a dark-grey colored roofing membrane.

The RH value below the exterior OSB decking is leveling between ~45% rh in summer up to ~92% rh during a few days in winter. Analogical to case 2, the critical limit for mold germination, 80% rh was exceeded, but no mold or wood decay fungi growth was detected during probing until now.

According to that, the relative humidity on the interface between cellulose and the internal vapor retarder

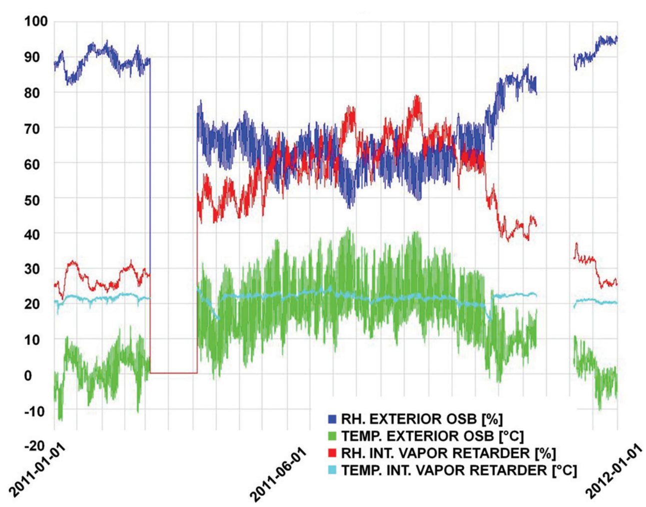

Figure 14 *Relative humidity and temperatures in test assembly 2 with light-grey roofing membrane.*

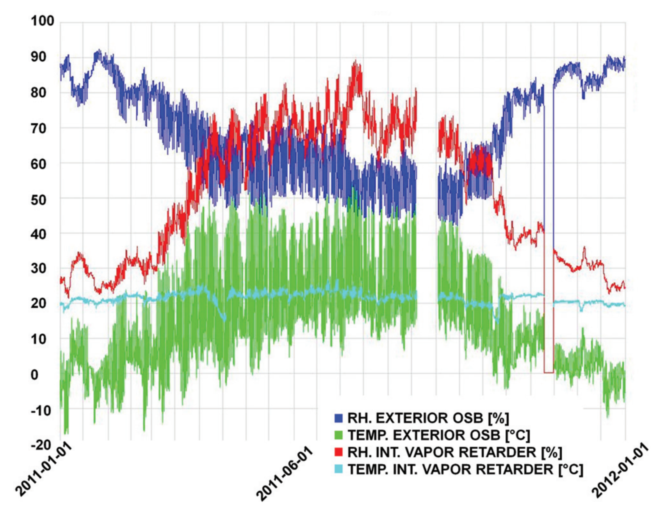

Figure 15 *Relative humidity and temperatures in test assembly 3 with dark-grey roofing membrane.*

was measured. The RH is leveling between ~22% rh in winter and ~88% rh during summertime. The higher RH gradient is founded in the higher solar driven diffusion due to the dark membrane surface. Although the critical limit of 80% rh was exceeded during higher temperatures, no mold related problems have been found.

DISCUSSION AND CONCLUSIONS

This paper presented initial results concerning the hygrothermal behavior of non-ventilated, highly-insulated timber-frame flat roofs with different waterproofing membranes in the climate of Austria. The investigations indicated that different colored waterproofing membranes are seriously influencing the external roof surface temperatures due to varying short wave absorptivity.

The varying surface temperatures are strongly influencing the moisture migration and accumulation and therefore the durability performance of low-sloped roof constructions. Darker membranes increase the temperatures in the exterior part of the roof assemblies and therefore optimize the solar-driven diffusion to the interior. Light-colored and especially white cool roofing membranes are reducing this effect, hence a drying of the roof construction is limited and moisture related problems are likely to occur.

Summing up, it is mentioned that aspects of thermal insulation and moisture control need to be investigated in common. A varying coloring of waterproofing roof membranes has to be considered as a critical factor, influencing the drying of unventilated low sloped roofs and modern computer based simulation models may be used to analyze the hygrothermal performance within the early design process.

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