Long-Term Hygrothermal Performance of Green Roofs

D. Zirkelbach **B. Schafaczek** **H. Künzel, PhD**
Member ASHRAE

ABSTRACT

Green roofs are becoming more and more popular because their thermal inertia, combined with latent heat effects, saves energy both in summer and winter and helps improve the microclimate in cities. Due to a multitude of influencing factors like moisture storage, freezing, evaporation, shading, reduced radiation absorption through the plant cover, etc., a simulation of the hygrothermal behavior of green roofs is still difficult.

In Germany, green roofs are often applied on so-called inverted roofs, where a vapor-retarding foam insulation is used above the roofing membrane in direct contact with the growth medium. Due to a more or less permanent moisture film beneath the insulation panels and a mostly moisture-saturated growth medium above, these insulation boards experience a continuous moisture accumulation during their service life. In numerous in-situ investigations of inverted green roofs, the accumulation of moisture was determined by periodical probing over a period of 10 years. Temperature and humidity sensors at several positions in the roofs served to monitor the transient behavior. Based on these tests, new models for the hygrothermal performance of inverted green roofs have been developed to simulate the moisture behavior of the foam insulation boards, depending on material properties and boundary conditions. Together with further experimental investigations, this model allows a detailed analysis of the long-term hygrothermal and energy performance of green roofs.

INTRODUCTION

The discussion about global warming in the last years also fuelled the use of green roofs (especially in cities) to reduce soil sealing, provide additional green spaces, and reduce the urban heat island effect. To reduce the risk of damaging the roofing membrane, green roofs in Germany are often applied on inverted roofs, where the roofing membrane is covered by vapor-retarding foam insulation boards.

Inverted roofs are common and well-proven assemblies that normally show good long-term performance. Only in cases of water-retaining or diffusion-retarding cover layers like green roofs or concrete slabs, a slow accumulation of moisture can occur within the insulation panels. This can be explained by the prevailing boundary conditions: rainwater that penetrates the insulation at the board joints leads to a permanent water film beneath the insulation boards. Under these conditions, the water content of the insulation increases in winter by vapor diffusion and condensation. In summer, the condensate can only dry out when the relative humidity at the interface between insulation and cover layer decreases; this is the case, for example, for gravel layers, while beneath a green roof growth medium or concrete pavers, the RH remains high most of the time even during summer. Figure 1 (Künzel and Kießl 1997) shows the simulated correlation between a potential moisture accumulation in the insulation and the relative humidity (RH) in the cover layer.

Only an average RH of below 85% ensures adequate drying to the upside to avoid any moisture accumulation in the boards. The closer conditions approach 100% RH, the faster is the moisture accumulation. This paper first investigates the measured conditions beneath the growth medium layers and the water content in the insulation boards by two different field

***D. Zirkelbach** is deputy head, **B. Schafaczek** is a researcher, and **H,M. Künzel** is head of the department of hygrothermics at the Fraunhofer Institute for Building Physics, Holzkirchen, Germany.*

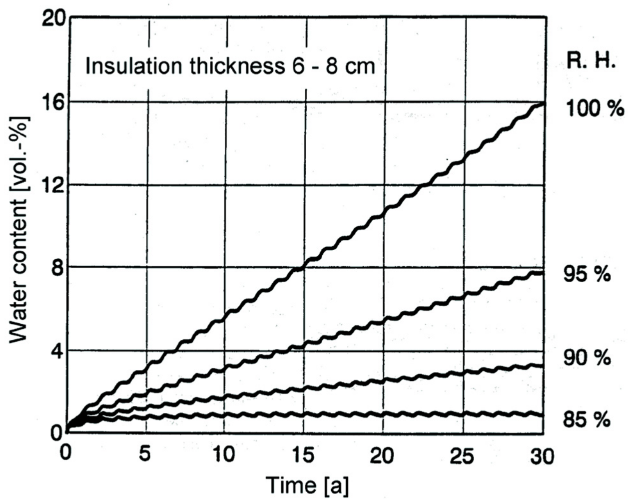

Figure 1 *Correlation between simulated moisture content in insulation boards of an inverted roof and RH in the cover layer directly above the insulation.*

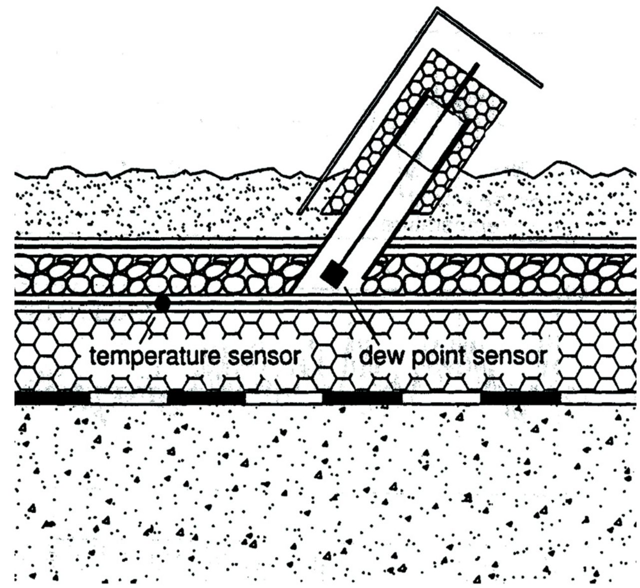

Figure 2 *Schematic figure of dew-point sensors in the drainage layer of the green roof.*

tests. In the second part, some new approaches are shown to simulate inverted green roofs, including the growth medium layer and the moisture film beneath the insulation boards. An accurate simulation of the green roof layers is still difficult, as multiple influencing factors have to be considered and adapted at the same time: moisture storage, freezing and evaporation enthalpy, self-shading effects of plants, increased moisture transfer due to transpiration by the plant cover, etc.

FIELD TEST SETUP

On the concrete slab with a size of 12 m by 12 m, above a heated laboratory, an inverted roof structure with different test fields was installed (IBP 1993).

The single test fields had a size of 3 m × 6 m or 3 m ×3 m; this allowed a partially parallel investigation of eight different roof systems. The first tests started in 1985, and the last ones were finished in 2004. Table 1 shows the different insulation thicknesses and cover layers above the concrete ceiling and the roofing membrane. The focus of the investigations of roofs 1 to 4 was on the moisture content in the insulation and its influence on the thermal conductivity of the materials. Therefore, samples of the boards were regularly (in the main test period, once or twice a year) taken from the roof and measured in the laboratory. Roofs 5 and 6 compared the moisture in the growth medium if applied on a normal gravel and a moisture-retaining expanded clay drainage layer, which should improve plant growth conditions. To determine the temperature and humidity directly on top of the insulation boards, temperature and dew-point sensors were installed in the middle of the test fields, as illustrated in Figure 2 (IBP 1996).

Temperature sensors were Pt 100 class A sensors with an accuracy of ±0.25 K. The dew point was measured with lithium chloride sensors installed in a vaportight plastic tube, which was open at the bottom end, thermally insulated and protected against solar radiation by an aluminium shield. The dew point sensors had an accuracy of ±0.75 K. The measurements were carried out continuously over a period of one year, with regular calibrations of the sensors. The dew-point sensors had to be regenerated from time to time because creeping of the lithium chloride film caused by high humidity changes can lead to lower readings.

EXPERIMENTAL RESULTS

Moisture Content in Insulation Boards of Roofs 1 to 4

The main test period lasted from autumn 1985 to summer 1992. Before disassembling the roofs in 2004, a final weighing of the insulation boards was performed. The measured values are listed in Table 2 as average value of normally two single measurements every year.

The moisture content in all different test roofs showed a (not always linear) tendency to slowly increase, depending on the different cover layers and material properties of the extruded polystyrene (XPS) boards. After 19 years, the water content in the insulation boards varied between 4.8 vol. % and 8.7 vol. % (48 to 87 kg/m^3). The increase of the water content is dependent on both the vapor diffusion resistance of the insulation and the humidity conditions beneath and above the boards in the roof. The water content in roof 1 with expanded clay in the drainage layer, which provides an additional moisture retention potential, increased faster and higher than in

Table 1. Test Roof Set up above Concrete Ceiling and Roofing Membrane

Roof	Construction
Roof 1 A/B 1985—2004	80 mm growth medium 50 mm drainage layer with expanded clay Filter fleece 100 mm XPS insulation (2 diff. manufacturers A/B)
Roof 2 A/B 1985–2004	80 mm growth medium No drainage layer Filter fleece 100 mm XPS insulation (2 diff. manufacturers A/B)
Roof 3 1985–2004	80 mm growth medium Filter fleece Drainage and water retention boards (EPS) 80 mm XPS insulation
Roof 4 1985–2004	80 mm growth medium Filter fleece Drainage and water retention boards (bituminous EPS) 60 mm XPS insulation
Roof 5 1995–1996	80 mm growth medium Filter fleece 50 mm drainage layer with gravel Protective fleece 100 mm XPS insulation
Roof 6 1995–1996	80 mm growth medium Filter fleece 50 mm drainage layer with expanded clay Protection fleece 100 mm XPS insulation

roof 2, with only growth medium on the insulation. In roof 1, the XPS of manufacturer B, with a higher vapor permeability, reached a higher moisture content of 8.7 vol. % after 19 years, compared to 4.8 vol. % in the material of manufacturer A. Also, in roofs 3 and 4, the additional moisture retention (here caused by the EPS drainage boards) led to a higher increase of water content compared to roof 2. At the end of the test period, both roofs reached 7.0 vol. % and 6.9 vol. %—quite similar values—while roof 4 had nearly twice the moisture content in the first years of the test until 1992.

Related to the increase in moisture content is an increase of the heat conductivity of approximately 15% to 25% (according to Zehendner [1979]) of the dry value at the end of the test period. This increase must be considered in technical approvals for materials in Germany to allow a correct evaluation of the long-term heat losses through such roof assemblies.

Temperature and Dew-Point Temperature beneath Growth Medium Layer

The measurements of roof sections 5 and 6 were performed to get more detailed information about the temper-

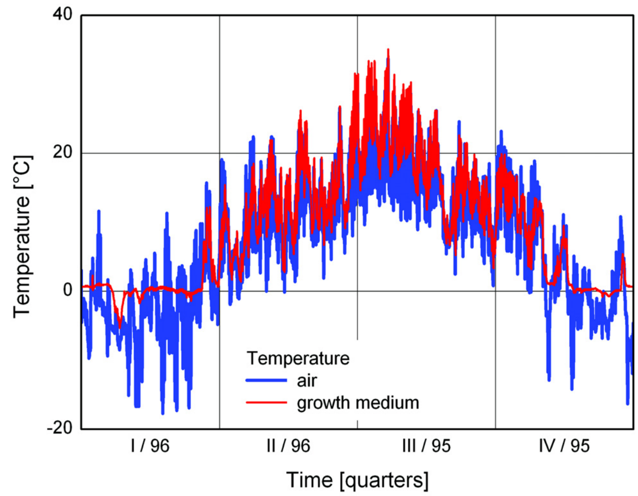

Figure 3 *Measured temperature beneath gravel layer of roof 5 in 1995 and 1996 (due to the test period, quarters I and II of 1996 were combined with quarters III and IV of 1995).*

ature and humidity conditions beneath the growth medium of green roofs. The measured temperature beneath the gravel layer of roof 5 is plotted in Figure 3. Compared to the ambient air temperature, it shows a much smoother course in winter. The values vary between minimum around –4°C in winter and maximum around 35°C in summer, compared to –18°C and 35°C in the ambient air.

Concerning the humidity in the growth medium, the results show that the best drying conditions prevail in July and August, when outdoor and roof temperatures reach their maximum values. July 1995 was particularly warm (monthly mean 19.2°C) and dry (total precipitation 40 mm) for the climate in Holzkirchen (680 m above sea level, close to the Bavarian Alps), while August (15.7°C, 230 mm) came close to average conditions.

Figure 4 shows the courses of the temperature (broken line) and dew-point temperature (solid line) at the exterior surface of the insulation in the different test fields and the daily amount of precipitation during these two months. In the green roof structures, the temperature and dew-point temperature coincide most of the time, even during periods of very little rain. That means that the relative humidity there is close to 100%. If the dew-point temperature falls below the ambient temperature, the relative humidity falls accordingly and signals drying conditions next to the insulation boards. The gravel in roof 5 does not retain rainwater like the expanded clay does, and consequently dries out more quickly. This leads to some shorter periods where the dew-point temperature falls a few degrees below the prevailing temperature, which corresponds to RH values below 85%. During these periods, a certain dry-out is possible, which can explain the differences of the moisture contents in the boards of the roofs 1 and 2.

Table 2. Measured Moisture Contents in the Different Test Roofs, Vol-%

Roof Type	1986	1987	1988	1989	1990	1992	1996	2004
Roof 1A	0.29	0.59	0.85	1.26	1.83	2.22	—	4.79
Roof 1B	—	1.28	1.86	1.74	2.19	2.62	5.18	8.70
Roof 2A	—	0.51	0.59	0.59	0.72	1.15	—	—
Roof 2B	0.26	0.64	1.06	0.98	1.01	1.52	1.81	—
Roof 3	0.60	0.84	1.20	1.13	1.68	2.16	—	7.01
Roof 4	1.56	2.23	1.99	1.67	2.30	5.16	—	6.94

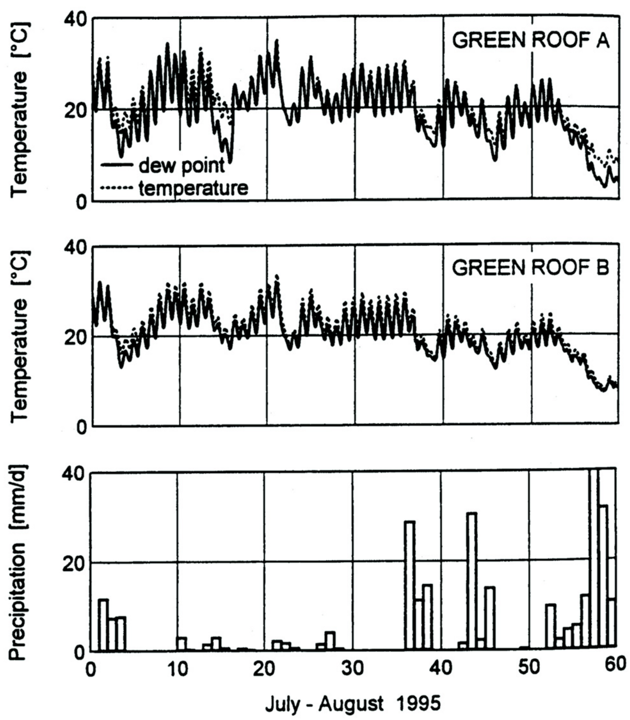

Figure 4 *Measured temperature and dew-point temperature beneath the gravel layer of roof 5 (top) and the expanded clay layer of roof 6 (middle), with the measured precipitation water (bottom).*

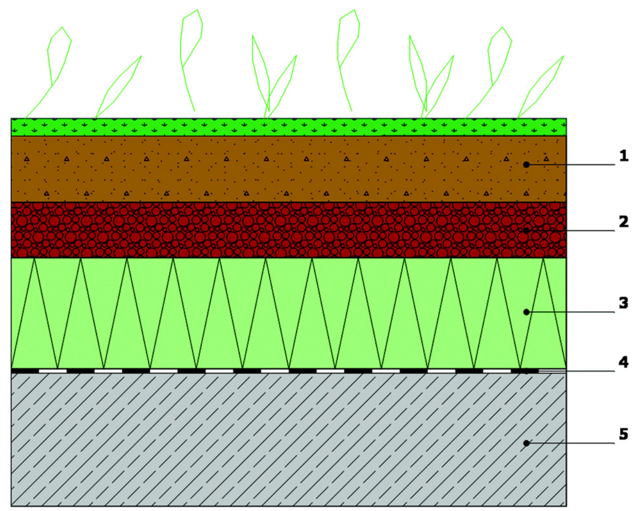

Figure 5 *Construction for the hygrothermal simulations of roof 1 and roof 5; 1: growth medium, 2: gravel or expanded clay brick, 3: XPS insulation boards, 4: roofing membrane, 5: concrete slab.*

Altogether, the results show that beneath the growth medium, the RH remains very high most of the time, with values close to 100%. Only without a water-retaining drainage layer can the RH fall below 85% RH for a short time during very warm and dry periods in summer.

SIMULATION OF INVERTED GREEN ROOFS INCLUDING GROWTH MEDIUM LAYER

To avoid a high safety margin for thermal conductivity in the material approval process, which covers all different materials and inverted roof types, manufacturers up to now have to provide field test measurements for their specific roof system. These field tests are expensive and time consuming. Therefore, a simulation of the roofs which indicates the potential moisture accumulation during the service life of the roof would be an interesting alternative solution. Such a simulation has to include the growth medium with all its influencing effects like moisture storage, freezing, evaporation, shading, and reduced radiation absorption through the plant cover.

The following simulations are performed by the help of the hygrothermal simulation tool WUFI® (Wärme und Feuchte instationär [transient heat and moisture]), which has been developed at the Fraunhofer Institute for Building Physics (IBP) for the past 15 years and validated by numerous laboratory and field tests (Künzel 1995). Based on typical values for a plant growth medium, the detailed properties for moisture storage, liquid transport, solar radiation absorption, etc. are iteratively adapted to fit the measured conditions with the simulation. Figure 5 shows a model of roofs 1 and 5, including the gravel, expanded clay, and growth medium.

In a first step, the values are adapted to the thermal conditions beneath the cover layers of roof 5. The outdoor climate

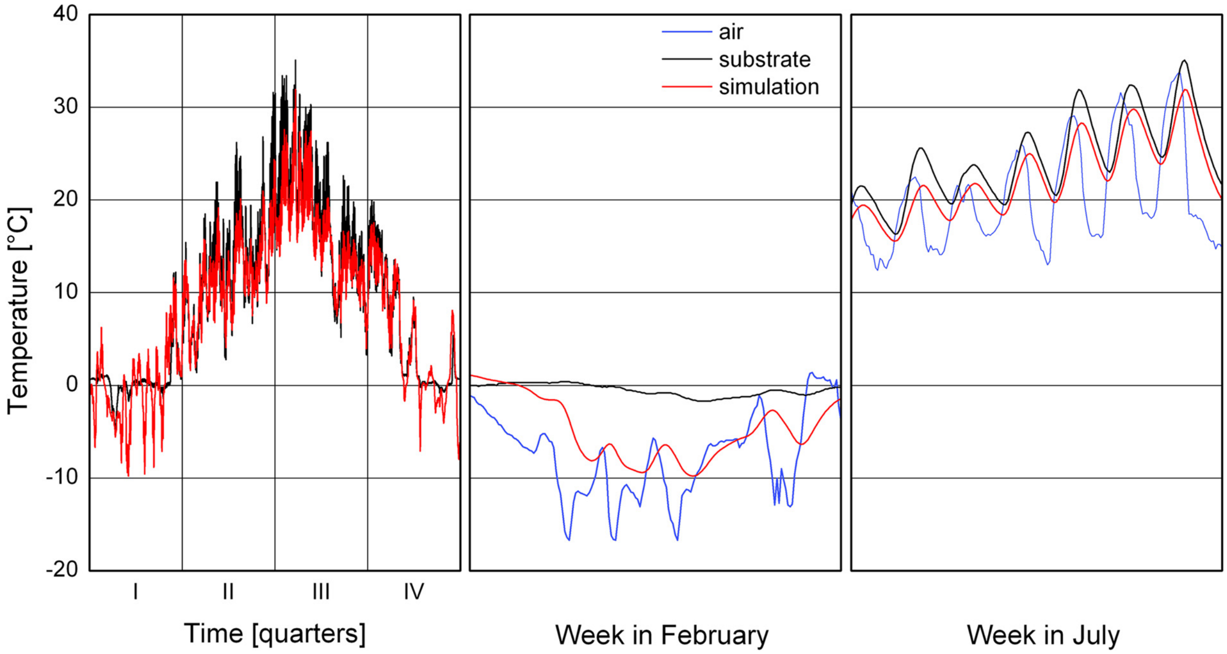

Figure 6 *Measured and simulated temperatures beneath the growth medium of roof 5 for the whole year (left) and for one week in winter (middle) and summer (right), in comparison with the exterior air temperature*

at the field test site in Holzkirchen has been recorded with hourly values since 1985. Therefore, the measured data can be used as outdoor climate for the test period of roof 5 in 1995 and 1996. Figure 6 compares the measured and simulated temperatures beneath the cover layers. A perfect agreement over the whole year could not be achieved: differences occur, especially in winter when snow is on the roof. This additional "insulation" leads to higher temperatures in reality, while the snow cover is not considered in the calculation. Therefore, the growth medium properties were adapted so that temperatures could fall below the minimum values in winter but must not exceed the maximum values in summer (i.e., the simulation remained always on the safe side). The resulting difference can be observed for an extreme situation in Figure 6 with the week in February: the measured black curve remains around 0°C, while the simulated growth medium temperature falls to –10°C and the air temperature even to –17°C. In July, the two curves fit quite well, with the simulated curve only slightly below the measured one.

The thermal approach would be sufficient for most roof assemblies that have a more or less vaportight roofing membrane. In case of inverted roofs, the moisture content in the growth medium is also of interest, as it has an important influence on moisture accumulation in the insulation boards. So in a second step moisture storage, liquid transport, and diffusion resistance of the growth medium has to be adapted to be able to simulate the moisture contents of the XPS boards measured in the field test. The moisture film beneath the boards is considered to be a moisture source in a 1 mm fleece layer, which deposits 1% of the precipitation water (limited to the free saturation of this layer). With this measure, humidity beneath the insulation remains above 99% RH all year round. For adaptation of the growth medium properties, roof 1 with growth medium on expanded clay brick was used, because here the humidity of the growth medium hardly fell below 99% RH and the most reliable material properties of the XPS boards were available. Two exemplary iterations for the adaptation of the insulation and the growth medium properties are shown in Figures 7 and 8.

The XPS insulation boards form during the extrusion process on the surface an extrusion skin with a significantly increased vapor diffusion resistance. In the laboratory, a 10 mm thick surface layer of the boards is cut off (thinner layers are difficult to cut) to determine the different diffusion resistances of the core material and the skin. In reality, the extrusion skin is thinner than 10 mm, and this difference can affect diffusion transport into the board. Figure 7 shows the simulated temporal development of the XPS moisture for different combinations of core and extrusion skin layer thicknesses, which all represent the same diffusion resistance value of the whole insulation layer. The best agreement between measurement and simulation, especially for the first years, can be achieved with an extrusion skin thickness of 1 mm.

Water retention of the growth medium at a high moisture level influences the thermal inertia, evaporation, and dry-out time. Figure 8 shows simulations with different free water saturation values (u_f) of the growth medium in a realistic range of 200 kg/m^3, 300 kg/m^3, and 700 kg/m^3 (2, 3, or 7 vol. %). A rather low free saturation of 200 kg/m^3 leads to the best agreement between the measured point and the simulated

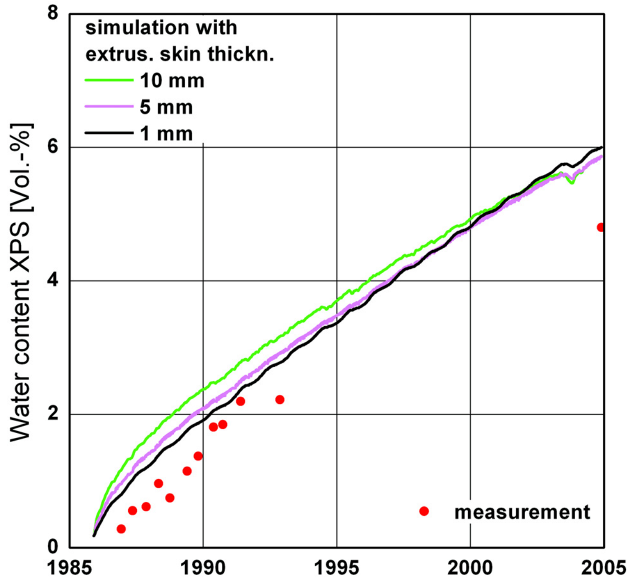

Figure 7 *Simulated water content in XPS insulation, depending on thickness of extrusion skin of XPS boards compared to measured values.*

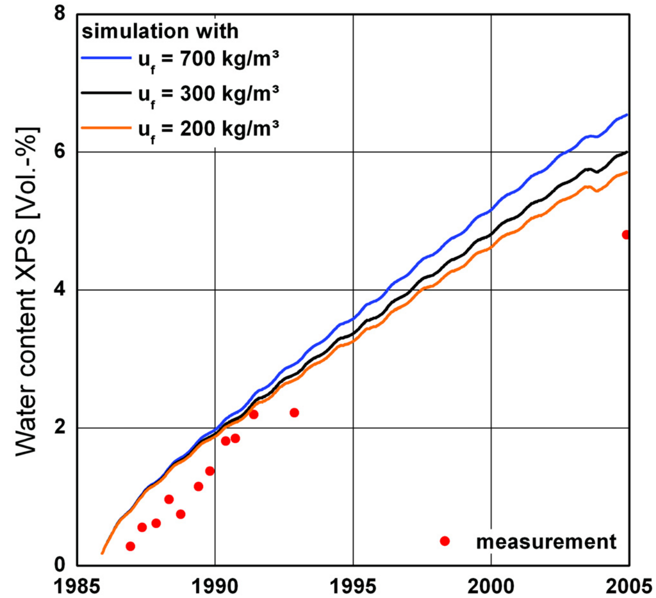

Figure 8 *Simulated water content in XPS insulation boards depending on free water saturation of growth medium compared to measured values.*

Table 3. Optimized Material Properties of Growth Medium

Material Property	Value
Bulk density	1500 kg/m^3
Diffusion resistance factor	5
Heat conductivity (dry)	0.9 W/(m·K)
Liquid transport coefficients D_{W0}, D_{WS}, D_{WW}	1E-10, 1E-6, 1E-7 m^2/s
Sorption values u_{80}, u_f	12,300 kg/m^3

curve; a value of 700 kg/m^3 seems to be too high. As a growth medium normally should provide a high moisture retention to minimize the watering demand, the value of 300 kg/m³ was used for the simulations. As in the model, precipitation water cannot be absorbed fast enough during intense rainfalls, so part of this rain would be neglected. To avoid this effect, which hardly occurs in practice (water normally runs off through the growth medium and not above), a moisture source on the bottom part of the green roof layer was introduced that deposits 40% of the precipitation water directly into the growth medium.

Figures 7 and 8 show that simulation of inverted green roofs, including an optimized growth medium and drainage layer, allows a realistic evaluation of water accumulation in the insulation boards. The approach is intended to remain on the conservative side and therefore leads to slightly higher values than measured in real life. Material properties used for the growth medium layer are given in Table 3. A first simulation of a green roof using these growth medium properties showed very good agreement with the measured temperature beneath the growth medium of a green roof in Vienna, Austria, even though the climate in Vienna is warmer and drier compared to the one in Holzkirchen. Further comparisons with measurements in Leipzig (eastern Germany), Kassel (central Germany), and Luzern (Switzerland) also showed satisfying agreement between the measured and simulated conditions beneath the growth medium. Consequently, the current approach for the material properties of the growth medium looks quite promising.

CONCLUSION AND OUTLOOK

The field tests confirmed the initial assumption of moisture accumulation in the insulation boards of inverted green roofs with more or less permanently humid cover layers. The moisture accumulation depends on the diffusion resistance of the XPS insulation and on the humidity conditions beneath and above the insulation boards. While a permanent water film has to be assumed beneath the boards, the growth medium can dry out during longer warm, dry periods in summer, especially if there is no additional layer with water-retaining drainage material or drainage boards.

The new approach of simulating the inverted roof, including the growth medium and drainage layer and using a moisture source beneath the boards, looks very promising. After an iterative adaption of the individual material properties, good agreement both for the temperature beneath the green roof and for the measured water contents in the insulation boards was achieved. Also, a comparison with measured temperatures beneath a green roof in Vienna and other European cities showed good agreement. The measured moisture content of the simulated roof 1A after 19 years was the lowest one of the four tested roofs, with 4.7 vol. %. Some further investigations of the three other roofs with different materials and drainage layers, as well as a comparison with measurements from different locations, will provide reliable and general input data to evaluate the hygric and thermal behavior of green roofs with the help of hygrothermal simulations.

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