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Thermal Performance Degradation of Foam Insulation in Inverted Roofs Due to Moisture Accumulation

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ABSTRACT

A normal roofing membrane is exposed to various mechanical and climatic impacts which can reduce durability and the service life of the membrane. In so called inverted roofs the membrane is situated beneath the insulation layer - which is ballasted with gravel or vegetated substrate. Thus, the sealing is protected versus the above mentioned damaging influences. Drawback of this solution is the direct exposure of the insulation to the outdoor climate. Therefore only materials with a high vapour diffusion resistance shall be used to minimize the entry of water into the insulation. However, the long term experience shows that also XPS boards experience some moisture accumulation especially in case where the cover layer remains humid most of the time. This slows down the drying process towards the top compared to gravel ballasted roofs. Based on long term field tests of green roofs this paper provides new approaches to simulate the hygrothermal conditions in inverted roofs. The model includes the simulation of the moisture behaviour of the substrate and an estimation of the amount of rainwater remaining at the interface between the sealing membrane and the insulation boards. Applying this model allows to asses the moisture accumulation in the insulation and the subsequent increase in the material's thermal conductivity over the life time of the roof. Considering the long-term moisture behaviour helps to specify the thickness of the insulation layer required to maintain the aspired level of thermal resistance over the whole service life of the roof.

KEYWORDS

Inverted roof, Foam insulation, XPS boards, Vegetated roof, Moisture accumulation.

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1 INTRODUCTION

Flat roofs may accumulate precipitation moisture due to leakages in the sealing layer which impairs their thermal performance. As the sealing layer – normally a roofing membrane – is exposed directly to the outdoor conditions degradation due to ageing or mechanical damage caused by the operation hold significant risks for defects and leakages. Changing the sequence of the construction layers by placing the insulation above the sealing membrane is one approach to improve the situation. In the so called inverted roof the membrane is well protected against both climate loads and mechanical impacts.

In Germany protected membrane (inverted) roofs have a long track record showing excellent durability of the sealing layer. However, the protection of the roofing membrane comes at the expense of higher loads for the insulation layer. Therefore water repellent and diffusion retarding insulation materials should be chosen. Predominantly extruded polystyrene boards (XPS) with high compression strength and a diffusion resistance factor of more than 100 are used. Initially it was assumed that the high vapour diffusion resistance would prevent moisture absorption or accumulation in the insulation boards. However, field tests and inspections of existing roofs showed a certain and sometimes continuous moisture accumulation of the boards especially in case of cover layers involving vegetation or pavers. The precipitation water which penetrates the insulation at the board joints results in a water film at the interface between the insulation and the roofing membrane which can hardly dry out in regions with higher precipitation loads. The water film on the warm side of the insulation leads to high water vapour pressure causing a diffusion flux into the boards and condensation during winter time.

If fast drying gravel serves as cover layer, the moisture in the insulation dries through the top side of the boards during dry summer periods - this compensates the moisture entry from the bottom side. In case of more water retaining cover layers like growth media for vegetated roofs or sand and split beneath concrete pavers, towards the top becomes impossible and moisture accumulation can occur. The moisture level in the insulation boards affects also the thermal conductivity, which has to be considered for the definition of the thermal resistance of the roof. Since the insulation layer of inverted roof lies beyond the water and vapour control layer of the construction its thermal resistance cannot be considered for energy performance calculations in Germany unless a technical approval for the roof system has been issued. In order to obtain such an approval it is necessary to check and prove the moisture content in the boards by long term field and in-situ tests. The paper shows that the long term water content in the boards can also be determined by the help of hygrothermal simulations depending on outdoor climate, building operation and the specific material properties of the insulation boards. Important factors for the reliability of the calculation results are the realistic modelling of the cover layers and their moisture behaviour as well as of the water film beneath the insulation board.

2 FIELD TESTS – MEAUSREMENT AND SIMULATION

2.1 Vegetated Roofs at the Field Test Site of the IBP in Holzkirchen

The reported investigations were carried out at the field test site of the Fraunhofer IBP in Holzkirchen, which is located on a plateau close to the Bavarian Alps in the south of Germany at 680 m above sea level. On the concrete slab sized of 12 by 12 m of a flat roof above a heated laboratory inverted roof structures with different composition have been installed. [IBP-Report 1993]. The individual test fields had a size of 3x3 m² - allowing parallel investigation of 8 different roof systems. The first tests started in 1985 - the last ones were finished in 2004. Table 1 shows the different insulation thicknesses and cover layers above the sealed concrete ceiling for three of the eight roof systems. The longest investigation period lasted approx. 20 years.

Table 1. Test roof assemblies on the top of the 120 mm concrete slab with vapor diffusion tight roofing membrane.

Roof (meas. period)	*Assembly*
Roof 1 (1985 – 2004)	80 mm growth medium 50 mm drainage layer (gravel, expanded clay) Filter fleece 100 mm XPS insulation Type A
Roof 2 (1985 – 2004)	80 mm growth medium 50 mm drainage layer (gravel, expanded clay) Filter fleece 100 mm XPS insulation Type B
Roof 3 (1985 – 2004)	80 mm growth medium Filter fleece Drainage and water retention boards (EPS) 80 mm XPS insulation

The focus of the investigations was the hygrothermal behaviour of the insulation layer, i.e the water content in the insulation boards and its influence on the thermal conductivity of the material. Therefore samples of the boards were regularly (in the main test period once or twice a year) taken from the roof and the water content of the boards was measured in the laboratory. To determine the hygrothermal conditions beneath the vegetated substrate – which is necessary to model the conditions in the cover layer later on - the temperature and humidity directly on top of the insulation was measured. For this purpose temperature (PT100) and dew point sensors (intermittently heated LiCl sensors) have been installed in the middle of the test fields as illustrated in Fig. 1 [IBP-Report 1996].

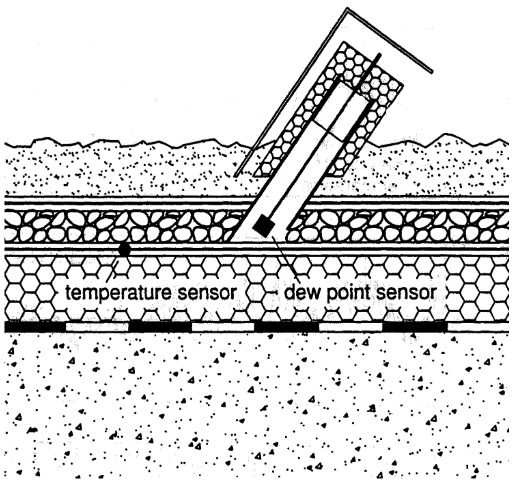


Figure 1. Schematic figure showing the positions of the temperature and dew point sensors in the drainage layer of the green roof.

The main test period lasted from autumn 1985 to summer 1992. Before disassembling the roofs in 2004 detailed moisture probing by weighing of the insulation boards was performed. The measured water contents are listed in Table 2 as average of normally two individual probings per year. The moisture content in all different test roofs showed a more or less continuous increase over the years. Depending on the different cover layers and material properties of the XPS boards the water content in the insulation boards varied between 4.8 and 8.7 Vol.-% (48 to 87 kg/m³) after 19 years. The increase in water content is a function of the vapour diffusion resistance of the insulation material and the humidity conditions beneath and above the boards. In roof 2 the XPS Type B with lower vapour diffusion resistance reached a higher moisture content (8.7 Vol.-%) after 19 years than XPS Type A in roof 1 (4.8 Vol-%). In roof 3 with EPS drainage boards the water content at the end of the test period reached 7.0 Vol.-%.

Table 2. Measured moisture content during the test period [Vol.-%].

Roof	*1986*	*1987*	*1988*	*1989*	*1990*	*1992*	*1996*	*2004*
Roof 1	0.29	0.59	0.85	1.26	1.83	2.22	-	4.79
Roof 2	-	1.28	1.86	1.74	2.19	2.62	5.18	8.70
Roof 3	0.60	0.84	1.20	1.13	1.68	2.16	-	7.01

As consequence of the rising moisture content, the thermal conductivity of the insulation material increases by approximately 2.8 % per Vol.-% (water content) according to [Zehendner 1979]. That means that at the end of the test period the heat conductivity of the XPS boards reaches between 113% and 125% of the dry state. This increase in conductivity should therefore be considered at the design stage to allow correct U-value assumption and evaluation of the long term heat losses through such roof assemblies.

2.2 Hygrothermal Modelling of Inverted Roofs Including the Cover Layers

By the help of modern hygrothermal simulation tools it is possible to simulate the performance of inverted roofs. While past calculations used constant humidity conditions above the insulation boards [Künzel & Kießl 1997], the following simulations include a new approach to model the hygrothermal performance of the cover layers (gravel or vegetated substrate) and the water films beneath the insulation boards. The new cover layer model includes all relevant effects such as moisture storage, latent heat of fusion and evaporation and in case of vegetation the reduced solar radiation absorption by partial shading provided by the plant cover. The following calculations are performed with the hygrothermal simulation tool WUFI® (Wärme und Feuchte instationär – transient heat and moisture) which has been developed at Fraunhofer IBP for the past 15 years and validated by numerous laboratory and field tests [Künzel 1995].

Table 3. Optimized material properties for a gravel cover layer.

Material property	*Value*
Bulk density	1400 [kg/m³]
Heat capacity	1000 [J/kgK]
Heat conductivity (dry)	0.7 [W/mK]
Vapor diffusion resistance factor	1 [-]
Free water saturation w_f	50 [kg/m³]

The hygrothermal material properties of a gravel layer are not so complex and could be adapted by previously done comparisons with field tests (not presented in this paper). Table 3 shows the optimized material properties of the gravel. In the gravel layer there is no capillary transport only drainage – therefore the rainwater is not absorbed at the surface but introduced over the thickness of the whole layer modeled by rain dependent moisture sources.

Table 4. Optimized material properties for a green roof growth medium.

Material property	*Value*
Bulk density	1500 [kg/m³]
Heat capacity	1500 [J/kgK]
Heat conductivity (dry)	0.9 [W/mK]
Vapour diffusion resistance factor	5 [-]
Liquid transport coefficients	
DW0, DWS, DWW	1E-10, 1E-6, 1E-7 [m²/s]
Free water saturation w_f	300 [kg/m³]

The material properties for the growth medium of an extensive green roof are listed in Table 4. The vegetated substrate will absorb rain water by capillary action. However, because the precipitation water cannot be absorbed fast enough in case of intense rainfalls, part of the rain water would be shed by the model originally designed to simulate the effect of driving rain; i.e. it would be assumed that it drains off the roof's surface the same way as driving rain drains of an exposed wall. To avoid this effect which hardly occurs in practice (the water will normally run off through the growth medium and not above it) a moisture source is introduced once again which deposits 40 % of the precipitation water directly into the bottom section of the growth medium. The above mentioned moisture film beneath the insulation boards is also accounted for by a moisture source in a 1 mm fleece layer which deposits 1 % of the precipitation water (limited to the free saturation of this layer).

Applying this model to a vegetated substrate layer under the climate of Holzkirchen with its high precipitation load, results in humidity conditions beneath the insulation which remain above 99 % RH all the year round. Due to the manufacturing process (extrusion of the polymer-gas mixture) the XPS boards have on both surfaces dense skins with significantly increased vapour diffusion resistance. In the laboratory a 10 mm thick surface layer of the boards was 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 much thinner but with the assumption of a 1 mm thick extrusion skin with a very high and a core with constant lower resistance a good agreement between the measured and simulated data could be achieved.

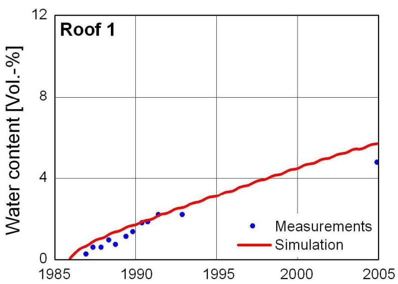


Figure 2

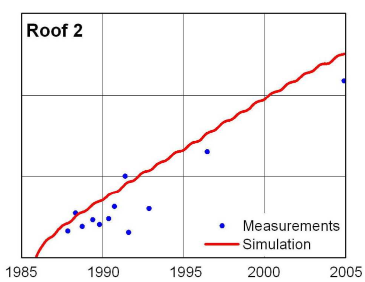


Figure 3

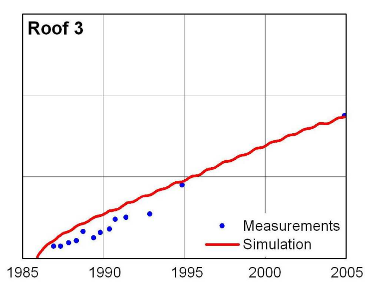


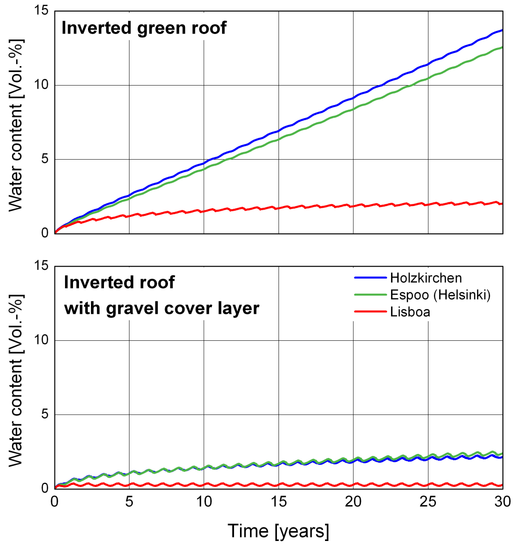
Figure 4

Measured and simulated water contents in the three test roofs at the IBP in Holzkirchen over the test period of approximately 20 years.

Figures 2 to 4 compare the measured and simulated water content in the XPS boards of the three different vegetated roofs at the field test site in Holzkirchen. The overall agreement is quite satisfying and the simulation as well as the field tests show a slow but continuous increase of the moisture content in the boards. The comparison of the model with further field investigation of inverted roofs at different locations in Germany, Switzerland and Austria confirmed the reliability of the approach and its transferability to locations with different precipitation loads. The mentioned investigations cannot be disclosed yet and will be published at a later stage.

3 LONG TERM BEHAVIOUR OF INVERTED ROOFS

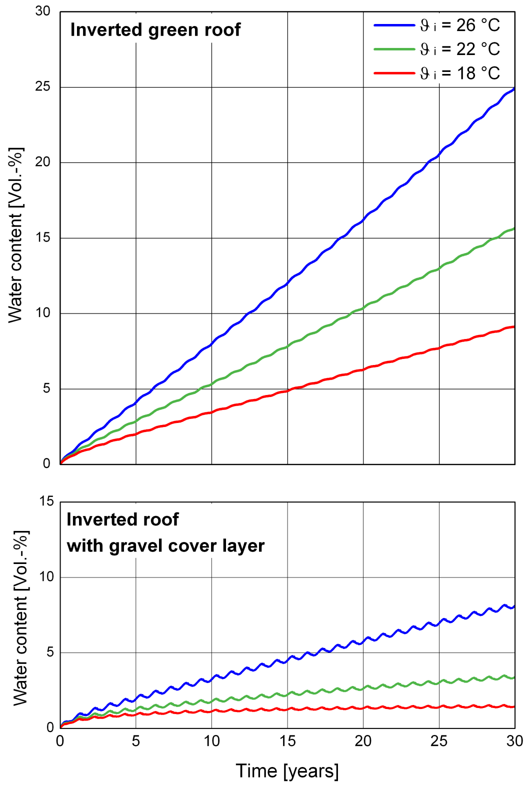
The optimization of the simulation approaches showed the following main influencing factors for the moisture content in the XPS boards: the type of the cover layer, the diffusion resistance of the insulation material (skin and core), the outdoor climate and the temperature level below the roof. Therefore simulations with different outdoor climate, indoor temperature levels and cover layers are performed. As roof construction serves the same assembly as in the field tests in Holzkirchen with 120 mm concrete slab, a vapour diffusion tight roofing membrane and 100 mm XPS insulation boards beneath the cover layers. As outdoor climate, weather files of the locations Espoo (close to Helsinki in Finland), Lisboa (Portugal) and Holzkirchen (Germany) are chosen to represent cold, moderate and warm European climate regions. For the three locations indoor climate conditions for residential buildings according to EN 15026 are derived from the local outdoor conditions. In Holzkirchen additionally a variation of the indoor temperature level (18 °C, 22 °C and 26 °C (e.g. swimming pool) constant over the whole year) is performed to check the temperature influence on the water content in the boards.



Figures 5 (top) and 6 (bottom). Simulated water content of the insulation boards in inverted roofs with vegetation (green roof Fig. 5) and gravel cover layer (Fig. 6) at Holzkirchen (Germany), Espoo (Helsinki, Finland) and Lisboa (Portugal) over a period of 30 years.

Figure 5 shows the water content in the insulation boards of an inverted green roof at the three different locations. While the water content only increases moderately in Lisboa to about 2 Vol.-% after 30 years, the increase is much higher in colder regions with 12 Vol.-% in Holzkirchen and 13 Vol.-% in Espoo. In Holzkirchen and Espoo the diffusion flux from the water film beneath the insulation layer penetrates the boards from the bottom side and can hardly dry out to the top into the permanently humid growth medium. In Lisboa the temperature gradient over the insulation layer is smaller due to the milder winter conditions and the growth medium can temporarily dry out during the hot and dry summer period. Both effects together lead to a significantly slower moisture uptake of the boards compared to the locations Holzkirchen and Espoo. The water content in the boards beneath the gravel roof (Fig. 8) are with less than 1 Vol.-% in Lisoba and around 2.5 Vol.-% in Holzkirchen and Espoo. The gravel cover layer having only little water retention can also dry out in Espoo and

Holzkirchen during periods with minor precipitation and thus allows also some dry out of the moisture in the insulation boards.



Figures 7 (top) and 8 (bottom). Simulated water content of the insulation boards in an inverted roof with vegetation (Fig. 7) and gravel cover layer (Fig. 8) at Holzkirchen with different indoor temperature levels of constant 18, 22 and 26 °C.

The temperature level below the concrete slab is mainly responsible for the vapour pressure in the water film beneath the insulation boards and thus for the diffusion flux into the XPS material. Figure 7 shows the water content in the insulation boards of green roofs in Holzkirchen for constant indoor temperatures of 18, 22 and 26 °C. While the 18 °C lead to approx. 10 Vol.-% after 30 years the values increase to 16 Vol.-% at 22 °C and even 25 Vol.-% at 26 °C. Again the conditions beneath the gravel covering are much more favourable with only 1.5, 3 and 8 Vol.-% for the three temperature levels.

4 CONCLUSIONS

Inverted roofs are well proven and reliable roof systems which provide a high durability of the sealing layer as the insulation boards protect the roofing membrane from climatic and mechanical impacts. However the insulation boards are exposed to the outdoor weathering with high humidity and precipitation water. The field tests show high humidities or even water films with more than 10 mm thickness beneath the insulation boards as a result of penetrating precipitation water being retained due to the usual unevenness of the underground. Thus a vapour diffusion flux into the boards cannot be avoided. Cover layers which can dry out during periods with little precipitation allow some drying of the boards towards the top of the roof which usually keeps the water content of the insulation low. For cover layers which remain humid most of the time like those of vegetated (green) roofs, moisture may accumulate in the insulation layer at different rates depending on outdoor climate, indoor temperature and material properties. The paper shows that hygrothermal simulations can be applied successfully to predict the long term water content in the boards and its influence on the thermal resistance of building assemblies. Due to the wide range of measured data and many uncertainties concerning for example the unevenness of the underground care has been taken to assure that the simulation model provides results which remain a little bit on the safe side.

Gravel covering shows a more favourable behaviour during drying periods which leads to only minor moisture accumulation in the boards even in case of colder outdoor climate. Only in combination with high indoor temperatures in winter, for example in swimming pools or buildings with industrial operation, the high vapour pressure beneath the boards results in a steeper increase of the insulation water content. Inverted roofs with vegetation experience significant moisture accumulation except in climates with warm and dry summer periods and mild winters. Under moderate and cold climate conditions especially in combination with higher temperatures beneath the roof the increase of moisture cannot be neglected and the influence on the thermal conductivity has to be accounted for. Insulation materials with a higher diffusion resistance show smaller water contents than more permeable materials. The simulation allows an evaluation of the different influencing factors material properties, cover layers and boundary conditions and help to maintain the aspired level of thermal resistance of the roof by adapting the insulation layer thicknesses.

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