EXPERIMENTAL AND NUMERICAL STUDY ON THE HYGROTHERMAL BEHAVIOUR OF NONVENTILATED WOODEN FLAT ROOF CONSTRUCTIONS WITH ECOLOGICAL BUILDING PRODUCTS

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ABSTRACT: Highly insulated and unventilated flat roofs in timber construction were more frequently applied in the last years. According to German standard DIN 4108-3 an internal tight vapour barrier is required for a verified construction, but also can easily cause moisture damages. At same time new building products, airtight construction, dry timber and wood based panels give new opportunities for safe and durable constructions. By long term laboratory examinations, numerical simulations and in-situ measurements for German climate conditions, design principles and recommendations which guarantee a durable use of wooden flat roof constructions in combination with high energetic efficiency, including ecological building products and without chemical treated timber according use class 0 of DIN 68800 were developed.

KEYWORDS: Flat roof, Durability, Moisture, Wood preservation

1 INITIAL SITUATION

Flat roofs are momentarily strongly in demand in the industry and administration building sector, but also by private house builders (Figure 1). Especially durable non-ventilated wooden flat roofs with compact and slim construction height, with high energetic efficiency, including ecological building products and without chemical wood prevention are of high interest.
Ventilated flat roof constructions often cannot assure necessary ventilation conditions, because of the marginal roof inclination. Moreover they are not architecturally interesting to due their large construction height.
German standards (DIN 4108-3:2001-07 and DIN 68800-2:1996-05) require for non-ventilated flat roof constructions either the arrangement of the insulation above the wooden load bearing structure or an internal tight vapour barrier ($s_d \geq 100$ m) for constructions with cavity insulation.
Many examples of built flat roofs have shown that constructions with tight vapour barriers can easily cause damages. Moisture input during the construction process or entering by air-leakages cannot dry out in summer through the tight vapour barrier [3].
Within the scope of the research project, data and knowledge of the hygrothermal behaviour for different constructions of non-ventilated wooden flat roofs were collected, by systematic long term and full scale outdoor measurements. On the basis of these experimental studies a validation of numerical calculations was carried out. The numerical simulations were done to identify limits of the construction variants and to evaluate climatical boundary conditions.

Figure 1: Residential building with wooden flat roof construction

The following subjects have been discussed within this project:
- How far can the usage of moisture-variable vapour barriers, oriented strand boards and external sealing

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layers with relatively low vapour diffusion resistance help to avoid moisture damages?

- Which criteria have to be complied, when using ecological materials such as cellulose insulation or oriented strand boards?
- What is the influence of external sealing and additional covering (colour of sealing, green roof, with gravel bearing, shaded) on the hygrothermal behaviour of the roof construction?
- Which conditions exclude endangering for timber and wood based panels and lead to abandon of chemical treating?
- Which CE labelled wood based panels according DIN EN 13986 can be used for these constructions?

2 BACKGROUND

Today's architects, planners and engineers are focus to sustainable, compact, non-ventilated, slim, energy efficient and highly insulated flat roof constructions under consideration of ecological building products and without chemical treated timber. These designs and performances often differ significantly from the requirements of German standards DIN 4108-3, DIN 68800-2 or similar technical regulations world wide.

Already in the 60s till 90s of the 20th century a strong demand for flat roof timber structures was recorded as a result of various public housing programs and architectural influences. Systematically studies of non-ventilated flat roof constructions with full cavity insulation aren't known from this period.

Notes as in German handbook for timber-constructions [1] showed simultaneously scepticism for non-ventilated, slim and full insulated flat roof constructions with both-sided tight vapour barriers ($s_d \geq 100$ m), because of endangering by diffusion and primarily unexpected infiltrated moisture, such as moisture of humid construction materials or entering by convection:

"Such constructions showed many structural damages by moisture in past, since a typical chemical wood preservation can not exclude these damages overall. Therefore, they should be applied only in exceptional cases " [1]. In details of German standard DIN 68800-2 (wood prevention) for the selection of wooden based panels in flat roof constructions similar explanatory notes are given. "Such structures can't recommend because of the possibility of moisture accumulation, such as vapour diffusion, air flow... " [2].

These statements show that current standardised non-ventilated flat roof construction with both-sided tight vapour barriers offers a large endangering for the timber structure and not be used by architect and planners by following reasons:

- Constructions with insulation above the rafters leads to thick roof structures,
- they do not comply with architectural requirements for slim structures,
- they are to complicate in erection and detailing and thus inefficient,
- novel moisture variable vapour barriers and wooden based panels can contribute to safe structures, but can't apply easily due to missing regulations,
- only the application of mineral wool insulation is possible without restrictions. The use of renewable and ecological insulation materials requires individual verifications by approvals,
- with European product standards and marking of wood based panels, the known classifications, which are required for the construction of flat roof constructions according to DIN 68800-2 disappeared .

Sensitized by occurred actual structural damages, the uncertainness regarding to non-ventilated flat roof constructions increase.

Current transient numerical calculations for coupled heat and moisture transport confirm such statements. Additional this tools shows that new materials can contribute to safe and durable non-ventilated flat roof constructions.

Renewable insulation offers in opposite to mineral wool capacity, to absorb and compensate increased humidity inside the structure for a certain period. Room sided moisture variable wood based panels and especially moisture variable vapour barriers increase the drying potential for the structure and offer an efficient way to dissipate moisture in the interior room during the summer. In addition the increased standard of air tightness and the regular use of kiln dried timber in the last period led to a lesser moisture influx in the construction. These statements show, that for non-ventilated flat roof constructions new and promising approaches and solutions appear, to exclude structural damages by moisture as a result of the current standards (both-sided tight vapour barriers $s_d \geq 100$ m) significantly.

A validation of these statements, as a result of numerical calculations, based on field studies and full scale laboratory examinations didn't exist until now. However these examinations are necessary to provide verification of the durability of non-ventilated flat roof timber structures.

One approach has been created in the present research project of Technical University Munich and Leipzig Institute for Materials Research and Testing (MFPA Leipzig).

3 EXPERIMENTAL RESEARCH

3.1 LABORATORY TESTS

The experimental study was carried out in an outdoor test building at MFPA Leipzig, where different non-ventilated wooden flat roofs were erected.

The utilised flat roof had a surface of 8 m x 5,5 m. The roof, which was inclined with 2°, was bordered by an attic. In order to avoid shading for the structure the test fields were always at 0,5 m from the attic.

The roof constructions differed in the inside vapour retardant layer (OSB/3 board respectively moisture variable vapour barrier), the insulation material (mineral wool respectively cellulose) and the external sealing (uncovered PVC sealing respectively covered with green roof). The constructive details of the individual examination variants can be taken from Figure 2 and Figure 3.

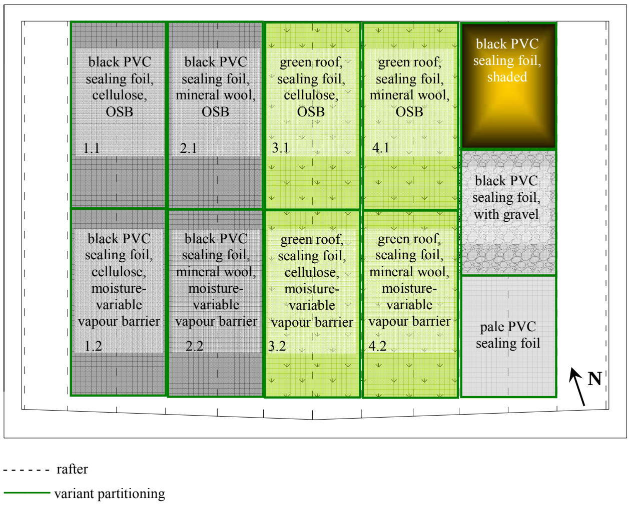

Figure 2: *Schematical top view of test building, variants of roof construction*

The roof construction was manufactured by kiln-dried timber rafters (80 mm x 220 mm), covered on top by a 22 mm thick OSB/3 boards and fully insulated in the cavities. The mean U-value of the construction was 0,2 W/m²*K.
There were eight measuring fields (four with black PVC sealing, four with green roof), each of them with an area of 3 m². The measuring fields were separated in the infilling areas from each other by vapour proof partition boards. Furthermore there were three measuring fields (with pale PVC sealing, with gravel, shaded) in order to determine the influence of sealing layer.
The interior room was air-conditioned with temperature of 20°C and relative humidity of 50 % in order to get ordinary usage conditions.
For a disadvantageous moisture content inside the construction and therefore starting conditions in the laboratory examinations the upper OSB/3 boards were conditioned to 12 M-%.

Figure 3: *Test building at MFPA Leipzig*

The following data were recorded in the test building: (see Figure 4)

- Outdoor and indoor climate
  - Temperature and relative humidity of outdoor air
  - Wind direction and wind velocity
  - Vertical rain
  - Global radiation
  - Temperature and relative humidity of internal air

- Hygrothermal conditions in the roof construction
  - Temperature under the sealing layer
  - Temperature and relative humidity in the "critical" section, between insulation and OSB/3 board (upper layer)

- Moisture content
  - Moisture content of rafters and of OSB/3 boards (upper layer)

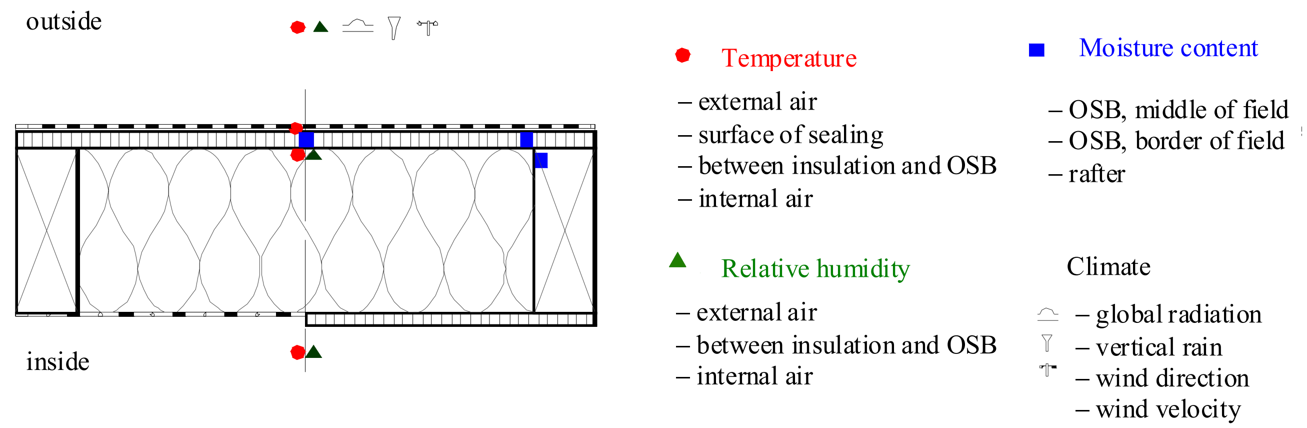

Figure 4: *Placement of measurement equipment*

3.2 FIELD STUDIES

In addition to the study in Leipzig, secondary examinations were carried out at existing objects with unventilated wooden flat roofs. All objects were examined visually as well some of them inspected for damages and moisture accumulation and equipped with measurement instrumentation inside the construction. Main goal of these studies was the enlargement of the existing data regarding to durability of non-ventilated flat roof timber structures and to for increase the data base of the laboratory test results.

3.3 NUMERICAL SIMULATION

Besides the recording and analysis of hygrothermal situation in laboratory tests (MFPA Leipzig) numerical simulations for all construction variants were carried out with a program for coupled heat and moisture transport (WUFI 4.0). Therefore, measured data of outdoor and indoor climate were used. In the focus of the simulation work was the validation of the program related to the used material properties and parameters to get better correlation of measurement and calculation results. Based on these validated numerical simulations additional calculations were done to identify limits of the construction variants and to evaluate acceptable climatically boundary conditions.

3.4 EVALUATION CRITERIA

Damages will occur, if parts of the timber construction or derived wood based panels, such as Oriented Strand Boards (OSB), show high moisture contents for a longer time period and if the dry out capability in summer is too low to lead away arisen moisture.
In the present research project, requirements and evaluation criteria have been derived from the application ranges of timber and wood based panels used and from the request to avoid the growth of mould fungus. A critical part in the examined flat roof constructions related to high moisture content and rot are the upper OSB/3 boards and the timber rafters.
The applied OSB/3 boards can be used in accordance to EN 300 in service class 2 of EN 1995-1-1. This class is characterised by moisture content of the materials corresponding to a temperature of 20°C and a relative humidity of the surrounding air only exceeding 85 % for a few weeks per year. In Germany the maximal moisture content under this climate conditions is expected by 18 M-% in accordance to DIN 68800.
The moisture content of the chemical untreated rafters shall not exceed the limiting value of 20 M-% in accordance to DIN 68800 for an assignment to use class 0. In order to avoid the growth of mould fungus, relative humidity in the critical section - between OSB board and insulation - should not exceed the limiting value of 80 % over a longer period.

4 EXPERIMENTAL RESULTS

4.1 LABORATORY EXAMINATION

The test results from the laboratory and field studies can be summarized as follows [4]:

4.1.1 Surface Temperature

The measurement results show a significant influence of short- and longwave - radiation for the examined fields and surfaces. Especially the uncovered PVC roofing foil leads during summer period to surface temperatures higher as outdoor air temperatures (Figure 5).
During the winter days with unclouded nights less surface temperatures comparable to outside air occurs (under- cooling).
The largest temperature fluctuation per day for summer and winter periods could be recognised for the uncovered black and light grey PVC roofing foils. The differences in temperatures can be caused by higher absorbent coefficient of black roofing foil in comparison to the grey roofing foil. Additional heat regulation layers (green roof, gravel) as well as shaded surfaces led to a reduction of surface temperature below the roofing foil, but also to decrease of the drying capacity of the construction in the summer time.

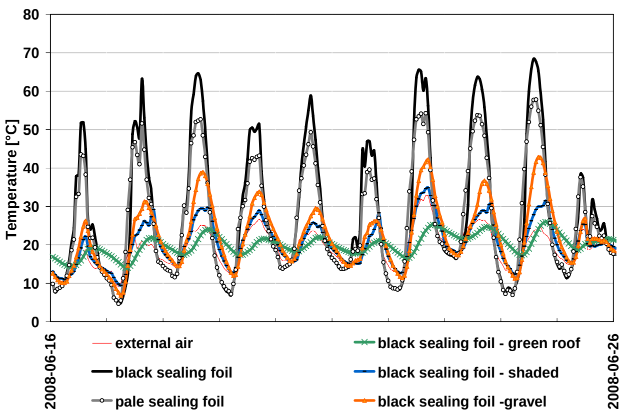

__Figure 5:__ Surface temperature under PVC sealing for examined fields; ten summer days

4.1.2 Influence of insulation material

Figure 6 and Figure 7 show the relative humidity between upper OSB/3 board and insulation. It should be mentioned that the blow in cellulose fibre - independent of roofing system - decreases the relative humidity in the critical areas significantly. The configurations (1.1; 1.2; 3.1; 3.2) showed in winter time in comparison to mineral wool infilling up to 15 % lower relative humidity levels. The capacity of cellulose fibre to store free water decrease the moisture content in the evaporation period (winter) for adjacent rafters and OSB/3 boards. This stored water is slowly but completely redrying in the summer time.

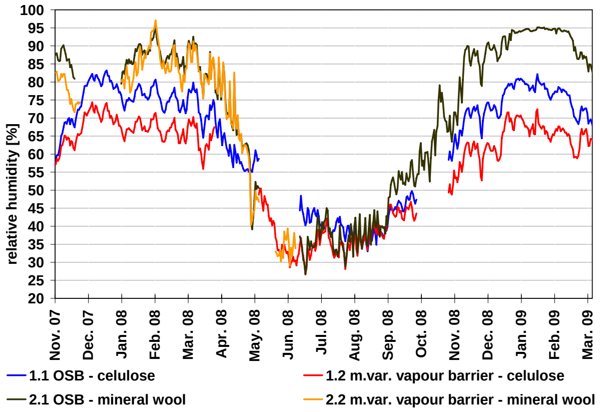

Figure 6: *Relative humidity between upper OSB board and insulation for fields with black PVC sealing, day-mean values*

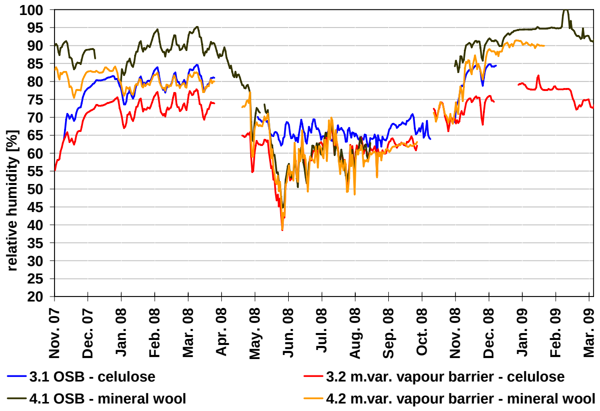

Figure 7: *Relative humidity between upper OSB/3 board and insulation for fields with green roof, day-mean values*

4.1.3 Influence vapour barriers

The graphs of Figure 6 and Figure 7 present also the beneficial effect of moisture variable vapour barrier receptive to 15 mm OSB/3 board as indoor diffusion checking layer. A comparison of the examined variants (1.1 versus 1.2; 3.1 versus 3.2 and 4.1 versus 4.2) shows that the higher diffusion resistance of moisture variable vapour barrier versus the OSB/3 during the evaporation period (winter), as well lower diffusion resistance in humid climate during dry out period (summer), leads to decrease of relative humidity and moisture content of assemblies in critical areas.

4.1.4 Green roof

The examined areas with green roof construction showed in the test period a higher humidity content inside the structure in comparison to uncovered areas, caused by decreased drying effect in summer due to the lower surface temperatures (lower vapour pressure gradient), see Figure 5. For this reason all variants with green roof starts at a significant higher humidity level in the second winter period. Already in November 2009 the examined variants with mineral wool exceed the limit of relative humidity of 85 %. The variant with inside OSB/3 lining and cellulose infill insulation reached this level in December 2009. By malfunction of used sensor further data for this variant are missing. Only the green roof construction with inside moisture variable vapour barrier and cellulose infill insulation shows a hygric uncritical situation, without endangering of construction.

4.1.5 Moisture content rafters

For clarification of question, whether endanger moisture contents in the rafters may appear, sensors on the outside edge of rafters have been attached (see Figure 4). Figure 8 and Figure 9 shows that the moisture content in the rafters for all examined variant was below the critical value of 20 M-%. Only the variants with mineral wool show the expected reaction of evaporation due to diffusion and achieve maximum values up to 18 M-%. The start conditions (moisture of rafter 15 M-%) and the air-tightness of construction ensure, that remaining diffusion processes have only a small influence of moisture content of supporting structure and exclude an endangering for the construction.

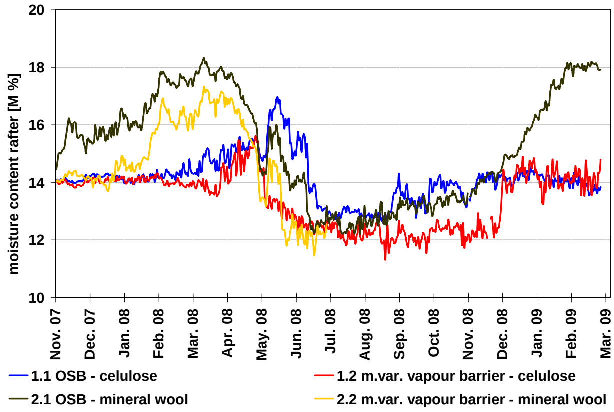

Figure 8: *Moisture content of rafters for fields with black PVC sealing, day-mean values*

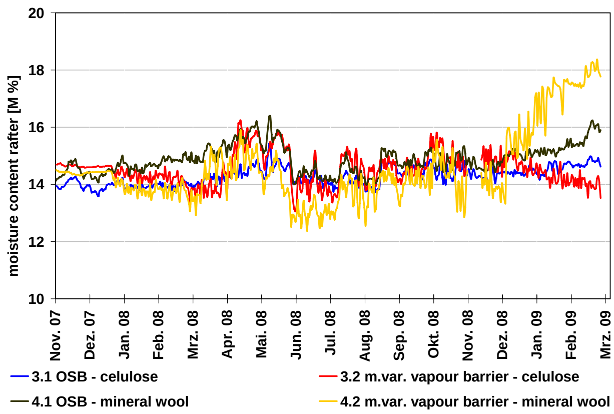

Figure 9: *Moisture content of rafters for fields with green roof, day-mean values*

4.2 HYGROTHERMAL CALCULATION

Measured data showed a very good coincidence with results of numerical simulation.

Figure 10 and Figure 11 show, as an example, a comparison of measured data and calculation results for variant 1.2 (black PVC sealing - OSB - cellulose - moisture-variable vapour check):

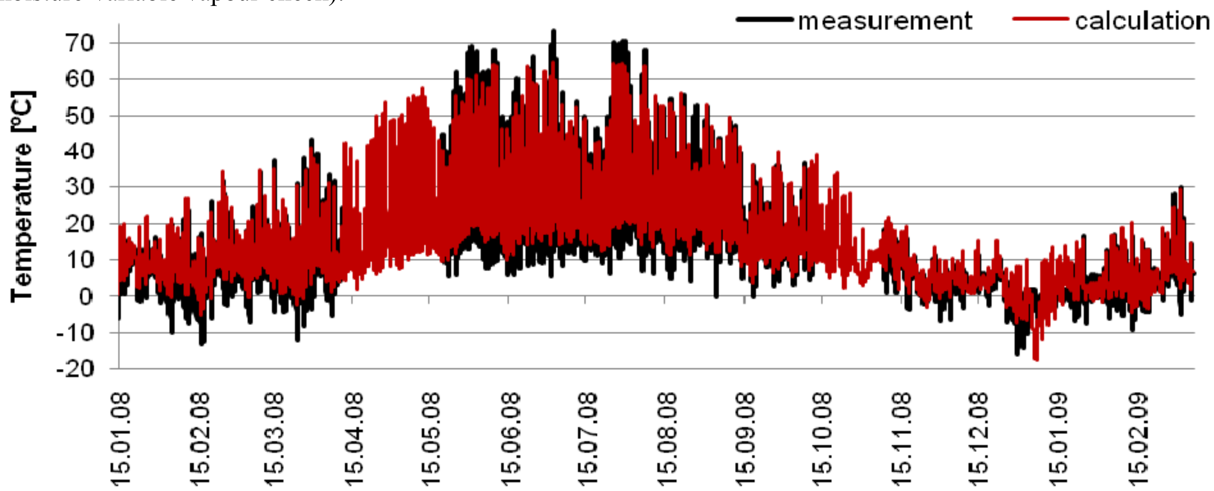

Figure 10: *Temperature between upper OSB board and insulation, field (black PVC sealing - OSB - cellulose - moisture-variable vapour check)*

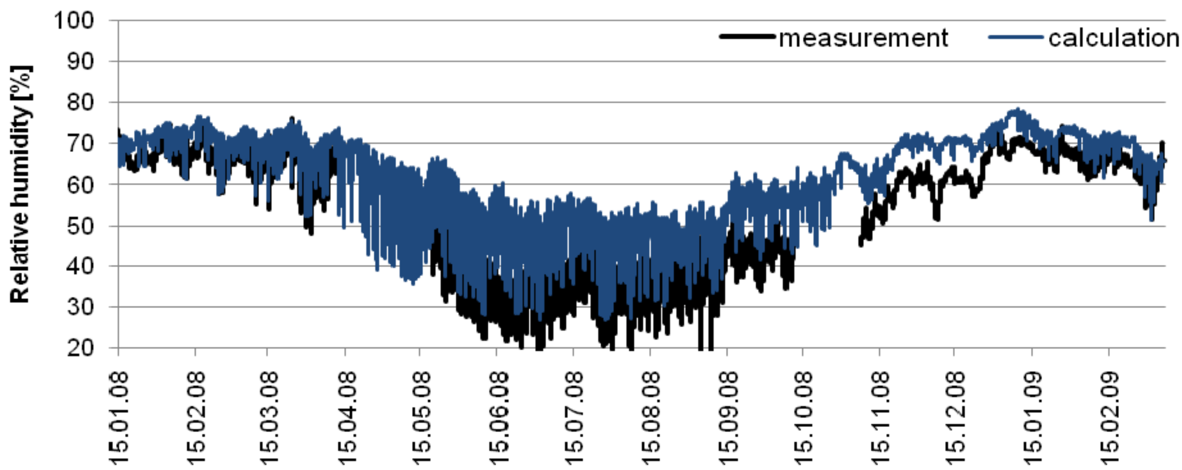

Figure 11: *Relative humidity between upper OSB board and insulation, field (black PVC sealing - OSB - cellulose - moisture-variable vapour check)*

On the basis of validated material data, further hygrothermal simulations (parameter studies) were carried out.

- Variation of outer climate (calculation for climate „Holzkirchen 1991“)
- Variation of inside climate (simulation of higher internal relative humidity because of e.g. cast plaster floor)
- Consideration of convective entry of moisture (50, 150 and 250 g/(m²) per evaporation period)
- Variation of outside sealing foil (calculation for pale PVC sealing and diffusion resistant sealing such as bitumen)
- Simulation of shading by adjacent buildings
- Simulation of structures above the roof (e.g. photovoltaic elements)

5 CONCLUSIONS

The present studies in the test building in Leipzig have shown that non-ventilated wooden flat roof constructions are able to perform without damages when considering certain constructive boundary conditions. Further knowledge on limits and usage conditions of the roof constructions could be derived from extensive numerical simulations. Studies on existing buildings with wooden flat roofs supplement the measurements in the test building and the numerical parameter studies.
The examined 8 variants differed largely concerning their hygrothermal behaviour.
The following constructions operated successfully and can therefore be recommended:

- Variant 1.2: Black PVC sealing - OSB - cellulose - moisture-variable vapour barrier

- Variant 1.1: Black PVC sealing - OSB - cellulose - OSB
- Variant 2.2: Black PVC sealing - OSB - mineral wool - moisture-variable vapour barrier
- Variant 3.2: Green roof - OSB - cellulose - moisture-variable vapour barrier

In singular cases, further studies must be carried out for:
- Variant 2.1: Black PVC sealing - OSB - mineral wool - OSB

The following variants cannot be recommended:
- Variant 3.1: Green roof - OSB - cellulose - OSB
- Variant 4.1: Green roof - OSB - mineral wool - OSB
- Variant 4.2: Green roof - OSB - mineral wool - moisture-variable vapour barrier

The following key results were gained:

- An absorbent insulation material, such as cellulose is able to store intermediately (buffer) moisture and therefore minimise the hygric stress of the construction, which can be caused by moisture input caused by construction process or by convection. Therefore the absorbent insulation materials should be preferred to e.g. mineral wool.
- A moisture-variable vapour barrier is advantageous compared to an oriented strand board due to its wider range of water vapour diffusion resistance.
- The usage of a black PVC sealing with a relatively low water vapour diffusion resistance (sd ~ 20 m) offers key benefits concerning hygric and thermal behaviour in comparison to the usage of pale PVC sealing or relatively tight sealing layers such as bitumen (sd ~ 300 m).
- An early and durable air tightness of the construction, already in the phase of erecting, reduces evaporation and high starting moisture contents.
- Void cavities inside the construction shall be excluded, to avoid movement of air and moisture by convective flow. Therefore high flexible insulation with adequate oversize or blown in insulation with high density can be recommended.

The authors advise: In addition to these specifications non-ventilated wooden flat roofs remain sensitive constructions. An increased care and quality assurance from planning to erection shall be guaranteed.

However:
If a correct airtight construction and durable external sealing is carried out under consideration of suggested materials for insulation and internal vapour retardant layer and if basic demands on boundary conditions are taken into account, non-ventilated wooden flat roofs work very well and operate without damages.

ACKNOWLEDGEMENT

The authors wish to acknowledge the considerable contribution made to this report by MFPA Leipzig.

This project was supported by German Society for Wood Research (DGfH e.V.) with funds of research program "Zukunft Bau" of German Federal Ministery of Transport, Building and Urban development (BMVBS) and of Federal Office for Building and Regional Planning (BBR).

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