Results of measured and simulated hygrothermal loads acting on mineral fiber insulation suggest a revision of durability test

D. Zirkelbach, Dipl.-Ing.
Department of Hygrothermics, Fraunhofer-Institute of Building Physics;
daniel.zirkelbach@ibp.fraunhofer.de, www.bauphysik.de

H. M. Künzel, Dr.-Ing.,
Head of Department of Hygrothermics, Fraunhofer Institute of Building Physics;
hartwig.kuenzel@ibp.fraunhofer.de

Ch. Bludau, Dipl.-Ing.,
Department of Hygrothermics, Fraunhofer Institute of Building Physics;
christian.bludau@ibp.fraunhofer.de

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SUMMARY:
Flat roofs with dark membranes experience higher thermal loads than most other building components. To increase also the moisture loads in the roof two litres of water per m² were inserted to a test roof on the field test site of the Fraunhofer IBP in Holzkirchen. The measured conditions in the roof serve to validate hygrothermal simulations which allow transfer the test to colder and warmer regions in Europe. As result the maximum temperature and moisture conditions and their coincidence occuring in an insulation layer of a building envelope in Europe can be determined. These results are compared to the climate conditions of current test procedures to determine the durability of mineral fibre insulation materials. The rather extreme temperatures and humidities (above 60 or 70 °C and 95 to 100 % RH) applied during these tests lead to a significant reduction of the tensile and compressive strength of glass fibre materials which cannot be observed in real life. Neither in the insulation layer of an ETICS - which was subject of earlier investigations - nor in the flat roof insulation layer such combinations of high temperature and RH were detected. A test procedure shall accelerate the normal degradation process but not make fail a solution which performs well in reality. Therefore a new test procedure is proposed which is closer to the real maximum conditions and should therefore lead to a more realistic performance assessment of the insulation material.

1. Introduction

Due to solar radiation and night time sky radiation flat roofs with dark roofing membranes experience higher thermal loads than other building components. Therefore this construction type was chosen to evaluate extreme hygrothermal conditions in mineral fibre insulations by the help of a field test and hygrothermal simulations. To increase the moisture content in the roof two litres of water per m² were inserted to the test roof on the field test site of the Fraunhofer IBP in Holzkirchen before closing the construction. The measured conditions in the roof serve to validate hygrothermal simulations and allow in a second step to “transfer” the test roof to other locations in Northern and Southern Europe. As result of this transfer the maximum temperature and moisture conditions and their coincidence occuring in an insulation layer of a building envelope in Europe can be determined.

These results are compared to the climate conditions of current test procedures to determine the durability of mineral fibre insulation materials. The rather extreme temperatures and humidities (above 60 or 70 °C and 95 to 100 % RH) applied during these tests lead to a significant reduction of the tensile and compressive strength of glass fibre materials which cannot be observed in real life. Aim of this study is therefore to determine test conditions that allow an acceleration of the natural aging process without damaging the insulation product in a way that will never occur in reality. The testing conditions have to be backed up by results from field tests and validated hygrothermal simulations to develop the basis for new test methods with more realistic temperature and humidity conditions.

2. Investigations

2.1 Field test

Subject of this study are the measured and simulated hygrothermal conditions in an insulated flat roof with the following composition from inside to outside:

- Load bearing wooden sheathing
- Vapour barrier (aluminium foil, sd > 1500 m)
- Insulation layer: 90 mm respectively 175 mm glass fibre boards
- Impermeable roofing membrane (elastomer bitumen)

A foto of the test roof in Holzkirchen and a schematic drawing of the roof construction with the measurement positions is displayed in Fig. 1. The placement of the sensors at the positions where peak loads are expected has been selected according to preliminary calculations. The temperature measurements are performed by using PT100 temperature sensors. The relative humidity is determined by capacitive sensors. Prior to the installation, all sensors are calibrated in the laboratory. The roof was set up at the field test site of the Fraunhofer Institute for Building Physics (IBP) in Holzkirchen (South Germany) in August 2006.

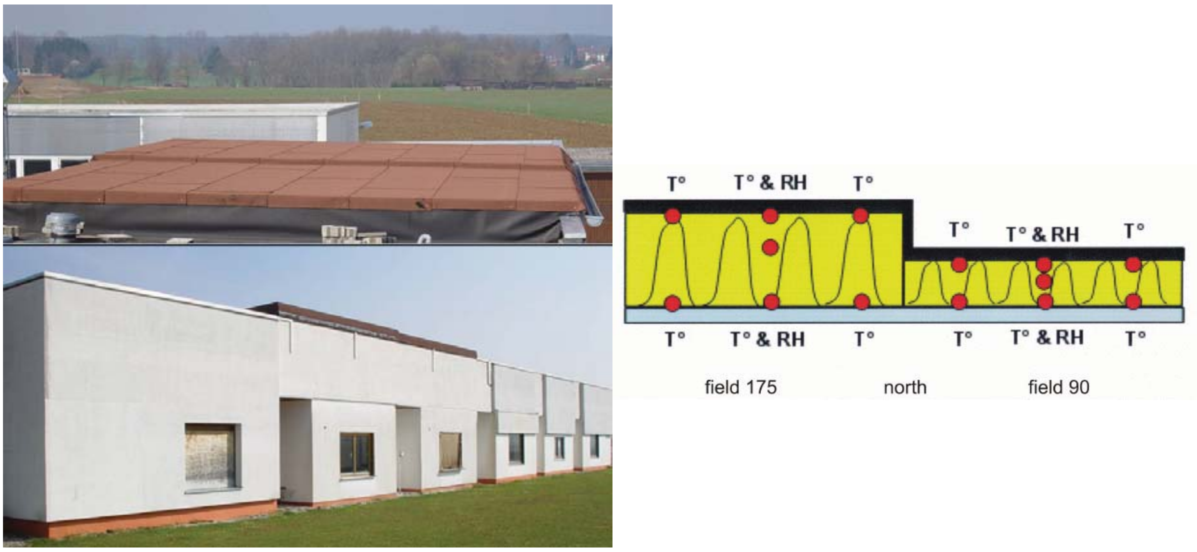

FIG. 1: Foto and sensor positions in the test roof (side and top view). The data recorded at the centre positions are used for validating the hygrothermal simulations.

In order to get an extreme scenario with a high initial moisture content about 2 kg/m² of water are added to the glass fibre insulation. It is expected that this moisture will be trapped in the construction between the vapour barrier and the vapour-tight roofing membrane. With the temperature variations during changing seasons or during a night and day cycle the moisture is expected to migrate between bottom and top of the insulation.

2.2 Hygrothermal simulations

The hygrothermal simulations are performed by applying WUFI® [Künzel 1995], which allows the transient calculation of the coupled heat and moisture transport in building components under real climate conditions. The model was developed at the Fraunhofer Institute for Building Physics and has been experimentally validated by comparison with numerous field tests. For the mineral wool a moisture retention curve based on the paper by Peuhkuri et al. [2005] and adapted to fit the measured results was used. The other material parameters are taken from the WUFI® database. As outdoor conditions the measured climate from August 2006 to January 2007 in Holzkirchen including solar radiation and long wave sky radiation from the atmosphere is used. As indoor climate serve the recorded temperature and humidity conditions in the attic space beneath the flat roof. The time period for which experimental and calculation results are compared lasts from August 2006 to January 2007.

If a good agreement between measurement and calculation in Holzkirchen can be achieved, the investigation may be broadened by repeating the simulations with climate conditions at other locations. The selected locations are Copenhagen in Denmark representing a Northern European climate and Naples in Southern Italy representing the warm regions of Europe. The meteorological data sets for Copenhagen and Naples are taken from the ASHRAE [2001] climate data which were compiled for building energy calculations. While the climate of Copenhagen appears to be mild compared to Holzkirchen, Naples shows higher air temperatures but not much difference in peak radiation. The indoor climate is assumed to be the same at all locations. According to the WTA-Guideline 6-2 [2004] sinusoidal curves between 20 °C / 40% RH in winter and 22 °C / 60 % RH in summer represent the indoor conditions in residential buildings with normal moisture load. However, since the roof is water and vapour tight the humidity conditions are rather irrelevant.

3. Results

3.1 Field Test

The field test described above is still ongoing - for the current paper a time period of six months from August 2006 to January 2007 is analyzed. The temperatures during the winter 2006 / 07 were quite moderate with only little snow. There were only a few days with temperatures below -5 °C while in a normal cold winter the temperatures can drop to -20 °C at times. The measured temperature and relative humidity within the construction are shown and discussed in comparison with the calculated results in the Figs 3 to 5. In the result diagrams the three sensor positions located at the centre of the roof sections are labelled from outside to inside with “exterior”, “middle” and “interior”.

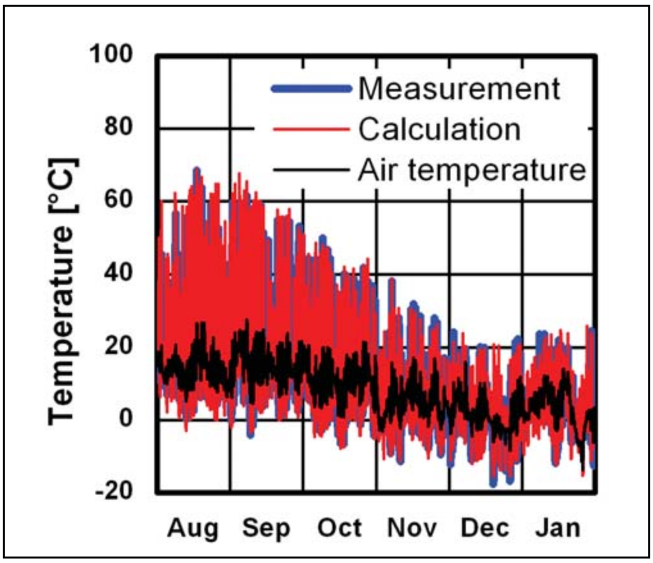

FIG. 2: Comparison of measured and calculated exterior surface temperature variations of the roof with 90 mm insulation and the outdoor air temperature at Holzkirchen.

3.2 Comparision of calculation and experiment

Figure 2 shows the measured (blue curve, sensor beneath the roofing membrane) and calculated (red curve) surface temperature of the roof with 90 mm insulation layer. The agreement between the two curves is very good - only sometimes the peak values show a small difference of two or three degree Celsius. The comparison with the outdoor air temperature (black curve) shows the strong influence of solar radiation (energy source during day-time) and sky radiation (energy sink during night-time) which is accurately captured by the new model for radiation and surface heat exchange in WUFI® version 4.1.

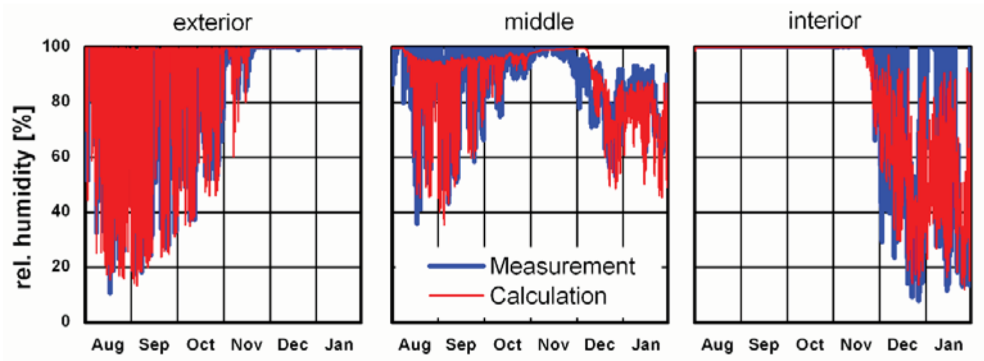

FIG. 3: Comparison of measured and calculated relative humidity variations at the three sensor position in the roof with 90 mm insulation under the indoor and outdoor climate conditions recorded during the test in Holzkirchen.

Figure 3 shows the relative humidity at the three positions within the insulation layer. The overall agreement between measured and calculated curves is quite acceptable. At the exterior position of the insulation the calculated and the measured curves coincide rather well. This is important, since the most extreme temperature and humidity conditions in the insulation layer are observed at the exterior sensor. In summer the RH at this position varies between 20 % at noon (when the sun shines and heats up the exterior surface) and 100 % during night. With lower temperatures and shorter days in autumn and winter the RH at noon increases and remains from midmonth of November permanently at 100 %. At the middle and the interior positions of the insulation layer the mean progression of the curves is very similar, but the spread of the measured values is slightly larger to both directions compared to the calculation. This difference may be due to a remaining uncertainty concerning the material properties (sorption isotherm, vapour diffusion resistance) of the glass fibre boards or the assumption of the initial water content in the roof.

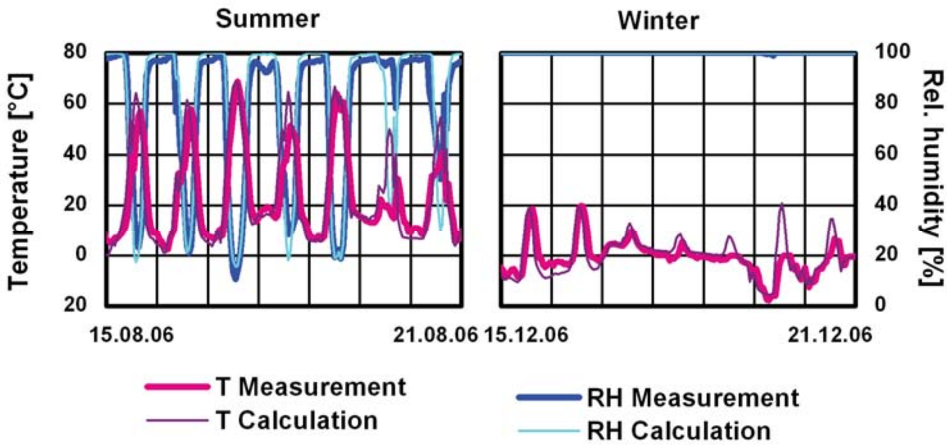

FIG. 4: Comparison of measured and calculated temperature and humidity variations at the exterior sensor position in the roof with 90 mm insulation for two se¬lected weeks in August and December.

A more detailed plot of the hygrothermal conditions for two single weeks in summer and winter (Fig. 4) at the exterior sensor position confirms the generally good agreement between simulation and experiment. The deviation in surface temperature on Dec. 20 is due to a thin snow cover of the roofing membrane which is disregarded in the simulation. An important observation concerning the durability assessment of the glass fibre insulation is the opposed variation of temperature and RH beneath the surface of the roofing membrane in Fig. 4. Every time, the temperature rises the relative humidity measured res. calculated for the same position drops in an inverse manner. That means high temperature and high RH never coincide at this point. The results of the roof with 175 mm insulation layer show less severe hygrothermal conditions with similar good agreement between measurement and calculation. Therefore these results are not plotted and discussed in this paper.

3.3 Evaluation of peak conditions

Laboratory tests have shown that the coincidence of high temperature and high humidity has a significant degradation effect on glass fibre insulation. Under dry conditions, a high temperature doesn't do any harm and a high relative humidity is not a great problem as long as the temperature remains low. Therefore, the measured and calculated hygrothermal conditions in the roof are displayed in a special graph where temperature and humidity are plotted against each other for time intervals of one hour.

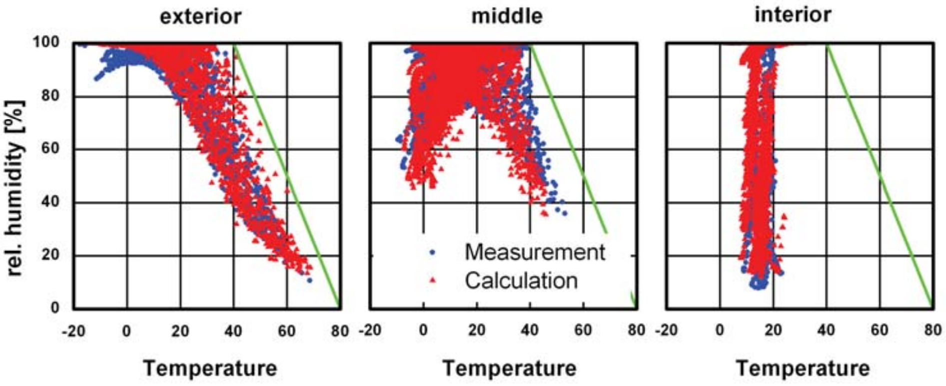

FIG. 5: Coinciding temperature and humidity conditions on an hourly basis measured and calculated at three sensor positions in the roof with 90 mm insulation. The green line represents the limiting curve for the hygrothermal conditions deter¬mined for the climate conditions in Holzkirchen.

Such a graph is shown in Fig. 5 for the three sensor positions in the roof with 90 mm thick insulation. The highest temperatures with more than 60 °C (maximum 70 °C) occur at the exterior position beneath the roofing membrane. However, the coinciding RH values remain very low, between 10 % and 30 %. The maximum RH of 100 % is frequently reached at all sensor positions. While the coinciding temperatures stay around 20 °C at the bottom of the roof (interior position) they can reach a maximum of nearly 40 °C in the middle and upper parts of the roof. The limit curve that will not be exceeded at any position in the insulation layer of the investigated roof can be drawn as a straight green line from 40 °C / 100 % RH to 80 °C / 0 % RH.

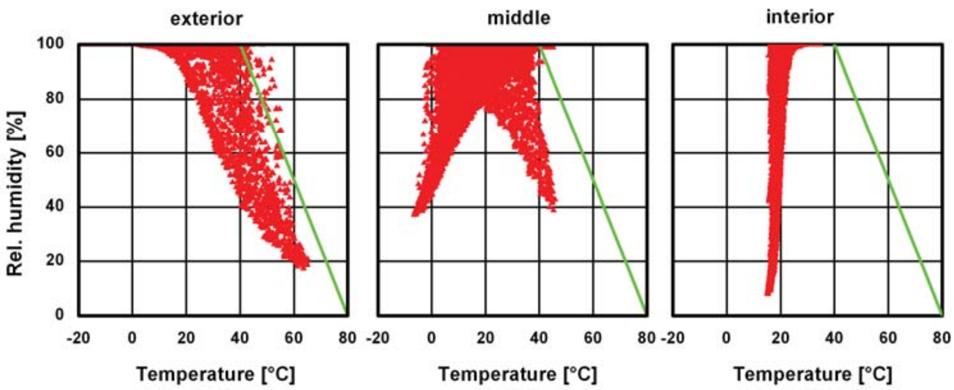

FIG. 6: Coinciding temperature and humidity conditions on an hourly basis calculated at three monitor positions within the roof with 90 mm insulation located in Copenhagen. The green line represents the limiting curve defined in Fig. 5.

The selected locations for the further hygrothermal simulations are Copenhagen and Naples. The plot of the calculated hourly RH plotted over temperature at Copenhagen is displayed in Fig.6. The results are very similar to the data of the flat roof in Holzkirchen (Fig. 5). However, the Copenhagen results for the exterior position come a bit closer to the limit curve (green line) and go even slightly over the limit a couple of times. In order to obtain more detailed information the coincident temperatures and relative humidities are classified in steps of 10 % RH starting with 50 % and steps of 10 K between -10 and +80 °C to analyse the different peak levels. The accumulated results are listed in Table 1. About 7700 hours a year a RH between 90 % and 100 % prevails, more than 3200 hours thereof at a temperature range between 0 and 10 °C and 1600 between -10 and 0 °C. In the higher temperature ranges the hours where RH exceeds 90 % become increasingly scarce. At Copenhagen the temperature within the construction never exceeds 70 °C. A temperature above 40 °C and a coincident relative humidity of above 80 % occurs during about 90 hours a year - this represents only 1.0 % of the service life of a roof.

TABLE. 1: Hourly classification of the simultaneous RH and temperature at the ex¬te¬rior position of the flat roof with 90 mm of glass fibre insulation for Copenhagen:

Temperature °C	Relative Humidity [%]					
	0 - 50	50 - 60	60 - 70	70 - 80	80 - 90	90 - 100
< -10						189
-10 - 0						1634
0 - 10						3262
10 - 20					1	1618
20 - 30			8	47	86	640
30 - 40	16	48	86	61	74	305
40 - 50	143	67	52	52	35	49
50 - 60	197	14	7	6	3	2
60 - 70	56					
70 - 80						
> 80						

The same hygrothermal analysis is repeated with the climate data for Naples. The relative humidity over temperature plot is displayed in Fig. 7. Compared to Copenhagen the values show a similar distribution - only the maximum temperature level in summer is 15 K higher but with a lower humidity of just about 10 % RH.

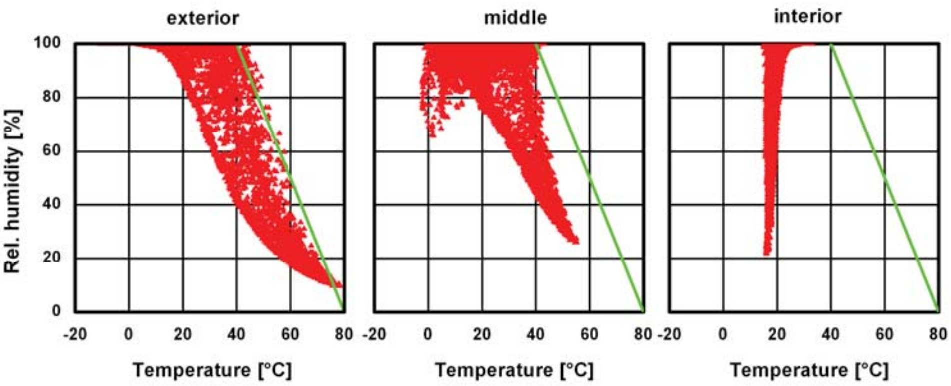

FIG. 7: Coinciding temperature and humidity conditions on an hourly basis calculated at three monitor positions within the roof with 90 mm insulation located in Naples. The green line represents the limiting curve defined in Fig. 5.

The hourly classification of temperature and humidity in Table 2 shows with about 6600 fewer hours between 90 and 100 % RH than the locations further north. Due to the higher surface temperature in summer the RH decreases faster during day. Most frequent in Naples are with about 2700 hours conditions from 90 to 100 % RH combined with a temperature between 10 and 20 °C followed by 2200 hours with the same RH at temperatures between 0 and 10 °C. Values above 80 % RH and 40 °C occur during less than 100 hours - so apart from the higher temperatures of 80 °C the number of hours in a higher range of RH and temperature differs hardly from the situation in Copenhagen.

TABLE. 2: Hourly classification of the simultaneous RH and temperature at the exterior position of the flat roof with 90 mm of glass fibre insulation for Naples:

Temperature °C			*Relative Humidity* [%]			
< -10	0 - 50	50 - 60	60 - 70	70 - 80	80 - 90	90 - 100
< -10						11
-10 - 0						599
0 - 10						2177
10 - 20					26	2659
20 - 30			37	56	166	778
30 - 40	41	108	53	67	110	348
40 - 50	240	80	83	41	49	48
50 - 60	384	26	10	4		
60 - 70	409					
70 - 80	148					
> 80						

4. Conclusion

The investigations show, that neither in Holzkirchen nor in northern or southern Europe a combination of RH above 95 % and temperatures of more then 60 °C can occur in vapour permeable insulation materials like mineral fibre – even not if there is a high initial water content in the roof of about 2 kg/m² like in the current case. The simultaneous occurrence of humidity conditions above 80 % RH and maximum temperatures between 40 and 50 °C at the most critical position within the insulation layer of a flat roof (beneath the roofing membrane) does generally not exceed 100 hours a year under European climate conditions. It should be noted that these conditions do not prevail continuously for several subsequent hours and they do not affect the entire insulation layer. They represent only short peaks that happen under particular weather situations at the most exposed part of the insulation layer, the zone directly below the roofing membrane. Other parts of the glass fibre boards experience less severe conditions.

Therefore iIt is proposed to define new durability test conditions based on the study presented here. Both the experimental results and the simulations have shown that coinciding peaks of temperature and relative humidity ranging from 40 °C to maximum 50 °C res. from 80 % to 100 % (average 90 % RH) add up to less than 100 hours per year. Consequently, there is good reason to set the durability test conditions to 50 °C and 90 % RH. However, the question concerning the duration of such test remains. Field tests periodically checking the durability of mineral fibre insulation in external wall insulation systems have shown that the greatest loss in pull-off strength happens in the first few month of service life. After that period the mechanical properties remain stable [Zirkelbach et al. 2005]. Continuous exposure of mineral wool to constant test conditions in the laboratory may show a slightly different picture (e.g. [Franke & Deckelmann 1999]), but they do not reflect the permanently altering hygrothermal conditions in the real world. The field tests indicate that there are periods (probably those with dominantly dry conditions) where the insulation material seem to recover its strength. This cannot happen during prolonged laboratory tests with constant peak conditions lasting 1000 hours or more. Thus, a test period in excess of the summed-up intervals of peak conditions occurring during a year in a real flat roof do not make much sense. It is therefore proposed to limit the test period to one week which is still on the safe side compared to the 100 hours of peak conditions actually occurring. For this conclusion, the long-term performance of glass fibre boards in flat roof constructions is assumed to be comparable to that of mineral fibre boards in external thermal insulation composite systems (ETICS), where the temporal development of the pull-off strength has been determined by field tests. In order to confirm this assumption field tests monitoring the compressive strength of glass fibre insulation in flat roofs should be carried out in future.

5. References

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