Durability of thermal insulation materials based on renewable resources – determination of hygrothermal loads as the basis to derive useful artificial test scenarios

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Abstract. Knowledge about the durability of thermal insulation materials is essential to establish constructions that meet the requirements concerning thermal, moisture and fire protection over the whole lifetime of the building, respectively allows to draw conclusions about necessary maintenance. In the underlying project, the relevant influencing factors and resulting ageing mechanisms (e.g. settlement/shrinkage, changes in the microstructure, degradation of additives, biological processes, etc.), as well as their effect on the essential characteristics (thermal conductivity, mechanical and moisture properties and fire behaviour) are identified for the most important groups of insulating materials made from renewable resources (wood fiber, loose filled cellulosic insulation (LFCI) and hemp). Based on this, suitable scopes of investigation are developed to prove durability for a service life of at least 50 years. This paper shows the results of hygrothermal modelling for a variety of representative constructions and locations all over Europe. To derive potentially useful test scenarios, special focus is given on the evaluation of the frequency distribution of hygrothermal conditions (couples of temperatures and relative humidity) over the lifetime, for the critical parts of the insulation materials. The simulation study evaluates the influence of the location (climate), use scenario (operation), construction and material types (adjacent materials, sorption and liquid transport behaviour etc.). Depending on the evaluation criteria, single hours (failure conditions) or average values over longer periods (development of decay or mould, strengths loss etc.) are considered. Also the ranges or amplitudes could be of relevance. Based on the results, accelerated lab ageing tests will be developed. On this basis, it will be checked in a later step, which scenarios actually lead to a change in properties and performance.

Keywords: Durability, Reference Service Life, Thermal insulation, Renewable resources, Hygrothermal modelling

1 Introduction

Natural fiber insulation materials are more frequently used in many European countries. A current research project [1] focuses on the long-term performance of such materials and aims to establish accelerated ageing tests which help to prove that the service life of the products can last 50 years or more in typical and critical assemblies without changing relevant material parameters. This paper presents a hygrothermal simulation study with WUFI® which is part of this project and determines the hygrothermal loads for different constructions using natural fiber materials as cavity, exterior or interior insulation. On that basis, both critical temperature and humidity conditions as well as critical hygrothermal cycles can be identified for different climate locations and operations throughout Europe. These conditions should be transferred into laboratory tests that represent the real loads of the whole service life within a few months and thus allow to identify suitable products for the different application fields.

2 Simulation study on the hygrothermal loads of natural fiber insulation materials in typical constructions in Europe

The conducted simulation study aimed to clarify realistic hygrothermal loads in natural fiber insulation materials applied in typical constructions throughout Europe.

2.1 Method – Hygrothermal simulation and material properties of natural fiber insulation materials

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 for the past 30 years and which is validated by numerous laboratory and field tests [2]. The model fulfills all relevant requirements from current standards like EN 15026, ASHRAE 160, WTA Guidelines 6-1 and 6-2, DIN 4108-3. To represent the hygrothermal performance of the different products, critical representative material data determined in a previous research project on wood fiber insulations [3] for the different product types and application fields are used to determine RH and temperature ranges for the lab tests.

2.2 Investigated typical constructions in Europe

Five basic constructions, summarized in Table 1 are simulated. The simulations include wooden constructions for pitched roofs, flat roofs and walls, which cover the vast part of constructions where natural fiber insulation materials are used. Also important, but with a pretty different hygrothermal behavior are walls with external thermal insulation composite systems (ETICS) for both wooden and masonry constructions as well as interior insulations on concrete and brick walls. The chosen constructions are commonly used either for new buildings or for retrofit or both in some cases. Construction details like insulation layer thickness, type of vapor retarder and breather membrane etc. were determined in consultation with the project committee, in which, among others, manufacturers, construction companies and building authorities are represented. This ensures that critical but typical components are considered, which realistically represent the materials' range of use and the hygrothermal stresses that occur. In each construction, one to three natural fiber insulation materials are investigated.

Table 1. Simulated typical constructions for Europe

Construction type		New building or retrofit	Insulation layer		
			Underlay /cladding	Cavity	Installation cavity
Wooden constructions	**Pitched roof**	new	A	B	-
		retrofit	A	*Mineral wool*	-
	Flat roof	new	A	B	-
		retrofit	A	*PU-foam*	-
	Cavity Wall	new	A	B	-
Interior insulation wall	concrete	retrofit		A/B	
	brick	retrofit		A/B	
ETICS wall	masonry	new	A	-	-
	wooden	new	A	B	B

notes: A: natural fiber insulation board
B: natural fiber flex mat or loose fill material

2.3 Influencing Parameters for the hygrothermal loads

To examine the range of the realistic hygrothermal behavior in typical constructions in Europe, the following influencing factors are examined during this simulation study by about 200 variations of 5 basic construction types.

Locations – outdoor climate

To consider the various climate conditions within Europe, the following four locations with different and rather extreme climatic characteristics are chosen: Helsinki, Finland in North Europe, with cold temperatures, low sun radiation gains and rather high RH values. Brest in France with moderate mild temperatures and very high precipitation loads due to the location at the Northwest coast of France. Holzkirchen in the South of Germany with a moderate cold climate with high precipitation loads and radiation gains, known as critical representative for Central European climate and location of the worlds' largest building physics field test site, as well as Bari at the Southeast coast of Italy, with a warm and dry summer period.

Operation - indoor climate

The indoor climate also affects the hygrothermal behavior of the constructions. Therefore, two indoor air moisture levels are used representing the normal design indoor climate with 5 % increased RH and in addition a high moisture level according to EN 15026. For the walls with interior insulation, only the normal indoor moisture level according to the same standards is used, as most manufacturers recommend their solutions for the use with render but without vapor retarder. Therefore, they are not suitable for a humid indoor climate but rather for renovating buildings with drier conditions, such as schools, kindergartens or office buildings.

Orientation

To simulate on the safe side, the critical orientations are used: North because of the lowest drying potential due to the lowest solar radiation gains and West because of the normally highest driving rain load for walls with water absorbing surface materials.

Other variations

The effect of shading by solar panels, which may reduce the drying potential, is also investigated for flat roof constructions, as their installation is becoming increasingly mandatory in many regions and cities. In some cases, different types of natural fiber materials are simulated to determine the dependency of the simulation result on these materials.

3 Evaluation of the simulation results

3.1 Evaluation criteria

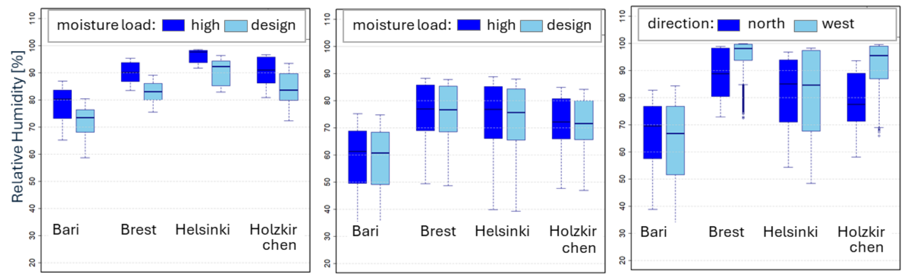
All simulations are carried out until dynamic equilibrium is reached. This means that the water contents in the constructions and in the single material layers only vary over the course of the year, but not from one year to the next. The conditions in the outer and inner 10 millimeters of each insulation layer are used for the evaluation, since the most critical conditions occur here.

The hygrothermal conditions in these areas are investigated in different ways: In a first simplified approach, humidity and temperature are considered separately, to check whether the effect of high separate loads is already having an impact on certain parameters of the materials. At least for the settlement of cellulose fiber insulation materials it is known that this can be caused only by moisture changes within the normal temperature range [4]. It is also conceivable that certain hydrophobic or binding agents could be influenced by the occurrence of high temperatures. Therefore, extreme values as well as typical variations throughout days or seasons are evaluated regarding the design of suitable accelerated ageing tests.

For other mechanisms, especially for biological degradation due to mold growth and wood decay, the duration of coinciding temperature and RH values is decisive. To address these three factors (temperature, humidity, time), the hygrothermal conditions at the investigated positions are evaluated graphically like shown in Fig. 2. To provide an overview over all investigated positions from all simulated cases, values such as mean daily or yearly fluctuations of temperature and relative humidity are derived from the simulation results and summarized as heatmaps (not shown here). Also, the exceedance of long-term biological growth limits for mold and decay fungi are provided to indicate such principal risks.

3.2 Exemplary Result Overview

Fig. 1 shows an overview of the humidity conditions for different exemplary constructions as boxplot. These graphs highlight the differences between constructions, where the insulation is adjacent to vapor-retarding layers on the outside like in a flat roof (i), adjacent to a ventilated cavity, like in the wood frame wall (ii) or in contact with a render exposed to driving rain like in the ETICS wall (iii).



(i) cavity insulation beneath a vapor retarding OSB and roofing membrane of a flat roof with variation of indoor moisture load.

(ii) cladding insulation behind a ventilated facade of a wooden frame wall with variation of indoor moisture load.

(iii) ETICS insulation boards with variation of the orientation between North and West (main driving rain direction)

Fig. 1. Boxplots of relative humidity in the outermost 10 mm of the insulation layer during the last simulated year at the four locations.

The moisture level in the flat roof insulation is generally clearly higher than in the wood frame wall. However, apart from this shift, the influence of the outdoor climate becomes visible: as colder the climate is, as higher rises the RH in the exterior part of the insulation. Pretty much the same applies for the wooden cavity wall on a RH level which is around 20 % lower compared to the flat roof. As expected, the higher moisture load in the indoor climate also increases the level of RH in the flat roof insulation beneath the vapor retarding OSB by around 10 % while hardly has any influence in the vapor permeable wooden walls. For the ETICS wall the rainwater influence becomes clearly dominant over the temperature conditions. The highest RH conditions are now observed at the Western orientation in Brest due to the high driving rain load, which increases the moisture directly by absorption on the exterior render surface and indirectly by the rainwater leakages deposited by a source on the inner cm of the insulation layer. The second highest RH level arises in Holzkirchen West, while the North orientation both in Brest and Holzkirchen as well as both orientations in Bari and Helsinki remain clearly dryer due to the lower driving rain load.

3.3 Influencing factors

After evaluating all results, the following influencing factors were found to be particularly relevant.

Vapor retarding layers on the cold side of the insulation
High humidity levels can be observed at the cold side of the insulation layer adjacent to a vapor retarding board or membrane. This applies in all climates and particularly affects flat roofs or pitched roofs with bitumen or sheet metal roofing. In these constructions, which needs to be watertight and at least vapor retarding, that influence cannot be avoided, but natural fiber insulations, used here, experience rather critical hygrothermal loads.

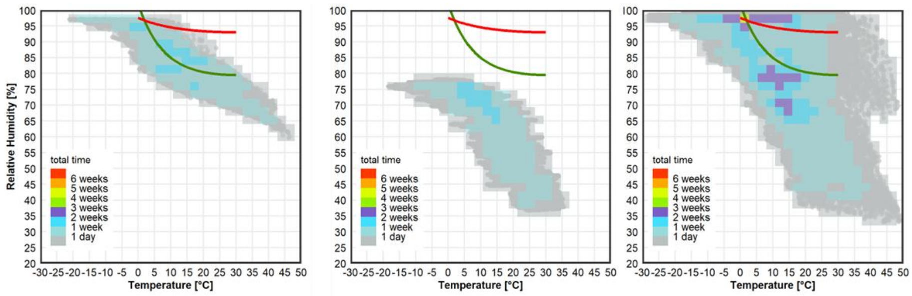
Rain water
Even higher moisture levels can occur in ETICS insulation beneath the exterior render in case of significant driving rain loads. Even low water absorbing renders on the outside lead to a high RH level in the insulation directly in contact with this render. If also rainwater leakages are considered in the simulation, like recommended in different standards, the moisture level is even more increased. A good rainwater protection level of the render system or the exterior wall surface is crucial for both walls with ETICS and interior insulations.

Indoor and outdoor climate
Cold climates lead to higher RH conditions at the cold outer part of the insulation materials – especially in case of constructions which are vapor retarding to the outside, like mentioned above. The same applies for higher moisture loads in the indoor climate. As higher the temperature and RH gradients between indoor and outdoor climate are, as higher is the resulting humidity level in the construction and thus also in the insulation layer. For outer insulation materials beneath vapour permeable or ventilated layers, as well as for ETICS insulation board where the rain load is significant, the indoor moisture load has a minor influence.

Material properties
Appropriate vapor retarders on the warm and vapor permeable layers on the cold side can reduce the negative effects of high gradients between indoor and outdoor climate. Moisture buffering materials on the cold side, like a sheathing in a wooden roof or a brick masonry outside of an interior insulation, can also reduce the RH in the insulation layers. Insulation materials with higher density normally provide also a higher moisture retention. That can be an advantage in vapor permeable assemblies, where they slow down the increase of RH caused by moisture fluxes from inside or outside. However, in vapor retarding assemblies this can become also a disadvantage, as higher moisture contents are initially built in.

3.4 Classification of the hygrothermal loads

For classification of the hygrothermal loads, the frequency distribution of the hygrothermal conditions at the four locations were combined in one graph per construction, exemplarily shown in Fig. 2. On this basis and in accordance with the influencing factors, the loads of all investigated cases are currently classified into six classes, as listed in Table 2.



(i) High load (underlay insulation board in flat roof with shading by solar panel)

(ii) Low load (cavity insulation under an underlay insulation board in pitched roof)

(iii) Very high load (ETICS insulation board with rain penetration)

Fig. 2. Frequency distribution of temperature and RH in the outermost 10 mm layer of the natural fiber insulation in different constructions. Conditions lasting more than one week per year are highlighted in different colors. The green curve indicates principle mould growth [5] and the red one wood decay risk [6]. In that range, higher requirements for the microbial resistance of the materials apply.

In wooden wall and roof constructions, the hygrothermal loads in the natural fiber insulations range from low to very high. While cavity insulations beneath an underlay board even don't exceed 80 % RH (Fig. 2, (ii)) the outermost area of underlay boards in pitched roofs, as well as both the underlay board and the cavity insulation in flat roofs can experience very high moisture levels, reaching nearly 100 % RH for several weeks of the year. However, also here a strong drying in warm and sunny periods can be observed with minimum values even below 20 % RH at temperatures over 50 °C (not shown here). This is where particularly extreme fluctuations in humidity and temperature occur. If the flat roofs are additionally shaded e.g. by solar panels, both overheating and overcooling is reduced, but the RH remains for longer periods at 100 % and only decreases to around 60 % (iii). However, at colder locations, shading cannot be recommended any more, as sheathing materials like OSB exceed all limit values for load bearing wooden materials. Therefore, the results of this construction are excluded for Helsinki.

In ETICS, the outermost area of the insulation beneath the render is decisive and the humidity regularly reaches 100 % RH after rain but also dries to 35 % RH or lower under warm conditions and sunshine. On the cold side of interior insulations, the humidity exceeds 80 % RH for more than 6 months in winter but normally remain below 95 % RH. For ETICS and interior insulations, therefore specific test scenarios will be required.

Table 2. Classification of hygrothermal loads for accelerated aging test

Type	Class	Hygro-thermal load	Hygrothermal condition	Material type and application
Wooden const-ructions	A	low	RH < 80 % RH	cavity insulation beneath underlay insulation board in pitched roofs
	B	middle	RH < 90 % RH	cladding board and cavity insulation in timber walls
	C	high	Short overrun of de-cay curve, high fluc-tuations 40 - 95 % RH	underlay boards in pitched and flat roofs / cavity insulation in flat roof without shading
	D	very high	Longer overrun of de-cay curve, up to 100 % RH	underlay board and cavity insulation in shaded flat roofs (fails in Helsinki)
ETICS wall	E	very high	long time around 100 % RH, large fluctuation 40 - 100 % RH	ETICS insulation board
Interior insulation on masonry	F	relativ high	more than half a year > 80 % RH	Interior insulation materials

4 Summary

The simulation study shows a wide range of hygrothermal conditions which can occur inside natural fiber insulations in construction which are commonly used in Europe. In this study the constructions were exposed to normal and high interior moisture loads as well as to climate conditions from the warm South via humid and rainy locations inbetween up to the cold North of Europe. The only designs omitted were those that clearly failed to meet the design criteria at individual locations, such as the shaded flat roof in Helsinki. With the identified hygrothermal conditions, accelerated ageing tests in the lab will be designed, which accumulate the extreme loads and the typical fluctuations during a service life of 50 years. These tests differ for the 6 defined exposure classes.

The tests will start with the more extreme conditions to check whether these will become problematic for certain materials or not. Step by step the loads can be reduced and test scenarios for every application class can be defined, as far as required to reliably verify the suitability of the products for the respective use.

5 Acknowledgements

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