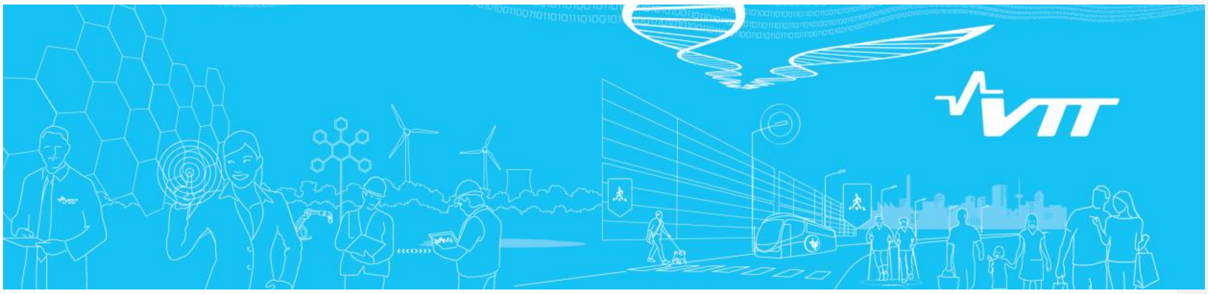
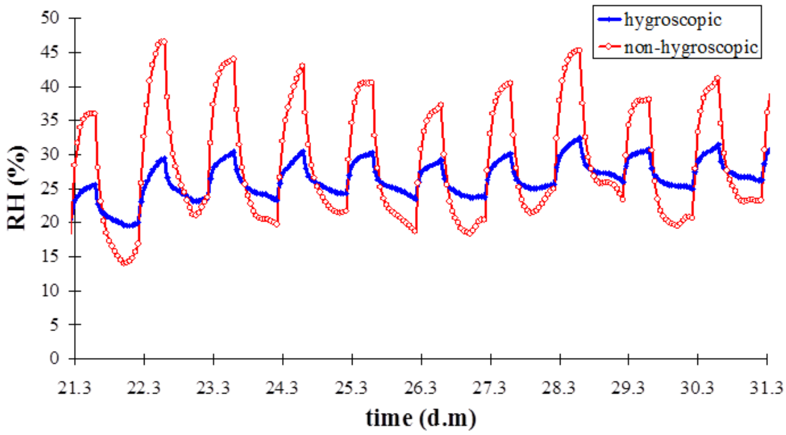


CLIENT REPORT

VTT- CR-00672-16 | 12.2.2016



Dynamic construction with cellulose fibre insulation

Authors: Tuomo Ojanen

Confidentiality: Confidential

Report name	
Dynamic construction with cellulose fibre insulation	
Client name, contact person and data	**Client reference**
Kehittämisyhtiö Witas Oy Markku Rautiainen InnoVapriikki Haapaniementie 16 44500 VIITASAARI	Contract date 22.10.2015
Project name	**Project number/Abbreviation**
Dynamic construction with cellulose fibre insulation	Cellulose fibre insulations

Summary

The purpose of this project has been the collection of the existing information on the advantages of hygroscopic properties of cellulose fibre insulations in terms of technical moisture functionality, as well as the interaction between the structures and interior air. This is intended to provide basis for determining the additional clarifications necessary while applying hygroscopic cellulose fibre insulations in various climate conditions of Europe and developing the most efficient related solutions.
The project also contains existing research information related to construction applications utilising cellulose fibre insulation, their advantages as well as functional requirements in order to overcome fluctuations of relative indoor humidity in dynamic circumstances. With regard to the functionality of energy-efficient structures certain analytical calculations have been performed related to the Finnish climate, as well as moisture conditions generated in dry apartments. Under typical moisture conditions, cellulose fibre insulation allows the building structure to maintain its functionality in terms of vapour transmission. The advantage of such a system is the ability to transfer moisture in both directions thus overcoming local fluctuations.
The transmission of vapour between the indoor air and the structure helps maintain humidity at agreeable levels, as the extreme conditions of a dynamic situation can be excluded thanks to the moisture capacity of the building structure. The transfer of vapour from a humid indoor climate to the drier building structure leads to a heating impact on the inner surface of the structure that is related to the change of status. In this case, the structure surface temperature grows and the conduction heat loss decreases. The impact of of drying and moisturising cycles over a year tend to balance out thus the real time dynamic affect enables energy saving as well as maintaining a agreeable humidity levels.
On basis of the gathered results, it is possible to present the objectives and tasks of the planned European cellulose fibre insulation project.

Espoo,4.2.2016

Author	**Reviewed by**	**Approved by**
Tuomo Ojanen Senior Engineer	Pekka Tuomaala Head Engineer	Riikka Holopainen Research Team Leader

VTT contact information

Tuomo Ojanen p. 0405173773, tuomo.ojanen@vtt.fi

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Abstract

The aim of this research was to summarize the published research findings about the hygroscopic properties of cellulose fibre insulation (CFI). Cellulose fibre insulation is a form of wood fibre insulation. Wood-based cellulose fibre insulation is composed of cellulose fibre treated with fire-retardant. Recycled newspaper is a common source of the CFI fibre which is used as in-situ formed loose fill applications with or without binding agents and as batts.

The summarized information shows the benefits of the hygroscopic properties of CFI from the moisture performance of structures and also from the interaction of structures and indoor air aspects. As a result, the need for additional research could be evaluated when aiming at the development of best solutions of CFI-structures to be applied under different climate conditions in Europe.

The existing research findings have given information on the moisture performance principles and benefits of CFI structures and also on the structural requirements to use the moisture buffering effect to smoothen down the changes of indoor relative humidity values during dynamic moisture load conditions.

The moisture performance of selected structures were analysed numerically under the climate conditions of Finland and using typical indoor load conditions of dry living space. Under these conditions the moisture performance of the analysed CFI-structures was safe. When compared to wood frame structures with vapour barrier, the benefit of the CFI structures with an air barrier open for diffusion is their ability to dry out in both directions, both towards outdoor and indoor air. The hygroscopic thermal insulation also smoothens down the local moisture content levels in the structure when compared to the performance of non-hygroscopic materials.

The moisture transport between indoor air and hygroscopic structures can improve the indoor air comfort by cutting down the occurrence of the extremely high and low relative humidity conditions. Under the exposure to indoor humidity conditions, moisture is then transported into the structure, which causes heat release due to latent heat effect. This warms up the indoor surface layers of the structure and the heat losses through the inside surface are decreased.

The yearly wetting and drying cycles tend to even out their opposite effects on heat flows, but the timely utilization of the dynamics may lead to energy savings in addition to the maintaining of the comfortable indoor conditions. The results of this work shall allow for the planning of the objectives and contents of a research project focused on the European applications of cellulose fibre insulation.

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1. Project description and objectives

Cellulose fiber insulation is a form of wood fibre insulation. Cellulose fibre insulation is cellulose fibre manufactured from newsprint paper, treated with fire retardants. It is used as insulation in loose form and in blocks. In loose form it is also installed with a binding agent allowing to obtain a permanent, non-settling insulation layer. In this report, a general term of cellulose fibre insulation is used (CFI).

The storage of moisture within a structure and its evaporation in different directions according to the current conditions is the most significant property of dynamic construction with cellulose fibre insulations. The hygroscopicity of cellulose fibre insulation, that is the material's ability to bind and release vapour, is the essential factor in this respect. This property can improve the structures humidity-specific functionality in various conditions and it may be used also for the maintenance of good indoor air quality. The moisture capacity of thermal insulation and other material layers equalizes the moisture flows and levels. Because of this, it is possible to use a vapour-permeable air barrier instead of a typical vapour barrier. This allows for the transfer of moisture from the structure back to the indoor air.

Moisture capacity or hygroscopicity as analysed using dew point observations does not define a structures functionality under typical, dynamic changing conditions. The operation of structures in situations corresponding with real conditions can be analysed most effectively by means of dynamic simulation technologies. This thesis can be then supported with empirical research.

The impact and operating conditions for the specific factors has been covered in previous surveys. In their course, the moisture safety of cellulose fibre insulations in various types of structures, as well as the technical interaction with the indoor air has been determined. The structure's hygroscopic capacity may be used for equalizing of indoor air moisture in dynamic situations, in order to keep it on favourable levels (1-8). As a precondition, one must ensure sufficient vapour circulation between the indoor air and the humidity-balancing material layer.

The objective of this project is to present, on basis of the existing research information and detailed analyses, the reasons that the special functionality of cellulose fibre insulations can be used in buildings, as well as the necessary additional research and development works. Humidity, its secure control within the structure, as well as the interactions with indoor air and their impact on the inside environment form the key factors.

Prospects have necessitated the initiation of a research project devoted to examining the functionality and applications of cellulose fibre insulation. As a departure point, we present this preliminary report which includes an overview of the current research data and certain targeted analyses of exemplary structures in terms of their functionality and interaction with indoor air. On basis of the results, it is possible to outline a new project, which will report comprehensively on the functionality of construction applications utilising cellulose fibre insulations in different climates and usage conditions, together with their impacts on the indoor climate.

2. Delivery

Work was carried out at VTT. Current situation data was gathered from existing research and the functionality of exemplary structures was examined by means of calculations.

The project doesn't have a management team, however the role of cellulose fibre insulation manufacturers has been significant for the delivery.

The project was initiated by concluding an agreement on 22nd October 2015 and lasted until 15th February 2016.

3. Current status

The mapping of the current status has comprised a summary of previous research. On this basis the need for further steps and development possibilities have been assessed.

3.1 Vapour-related functionality

The vapour-related functionality of well-insulated cellulose fibre insulation structures in the Finnish climate and in normal vapour exposure in dry rooms of residential buildings have been recognised as advantageous in many surveys.

One of the previously performed functionality surveys is the Termex Zero wall structure, the results of which were published in /9/. The vapour-related functionality of a ventilated Termex Zero passive wall structure ($U = 0.11$ W/K m^2) has been recognized as safe in the Finnish climate and under the moisture load generated during normal residential use. The air-tight layer of the structure was formed by special cardboard and pine veneer.

Cellulose fibre insulation does not increase risks associated with humidity in dry rooms in houses in comparison to other fibre-based insulations. In a structure filled with cellulose fibre insulation, a vapour-permeable air barrier may be used, other than a typical vapour-tight foil. This, together with the proper processing of the inner surface enhances the vapour transmission between the indoor air and the structure.

This interaction can be significant in the case of a hygroscopic structure, providing new possibilities in terms of functionality. It also serves to ensure the functionality of the structure in various vapour exposure conditions both inside and outside the building. Structures that dry in both directions enable summertime drying towards the indoors. This advantage may be even more important in warmer climates than Finland. Another factor is the moisture interaction between the structure and the interior in terms of indoor air conditions.

It is still necessary to clarify among others the following impacts:

- The impact of the specific structure layers on the vapour-related functionality, especially the vapour permeability properties of the inner air barrier
- Functionality in different climates
- Functionality in different indoor air conditions (summertime cooling, high vapour exposure, etc.)
- Impact of cellulose fibre insulation and other structure properties, as well as their optimization in order to correspond with the vapour exposure caused by climate conditions

In chapter 4 the functionality analyses of selected exemplary structures in the Finnish climate.

3.2 Humidity interaction between the structure and indoor air

3.2.1 Significance of indoor air humidity

The indoor air moisture influences the healthiness, quality and thermal comfort of room air (Fig. Fig. 1 and Fig. Fig. 2) /10 – 12/. The experienced indoor climate comfort depends among other factors on the air and surface temperature, as well as air humidity, flow speed and quality. Provided that the other factors are on a normal level, the humidity of 30-55 % RH normally indicates a comfortable atmosphere.

In addition, also the user's age, weight, gender, heat generated at work, clothing etc. may affect the experienced thermal comfort. The indoor thermal comfort may be evaluated by means of calculations with the use of various methods /13/ which subsequently may be also applied to the analyses of the impact of hygroscopic building structures on the living comfort.

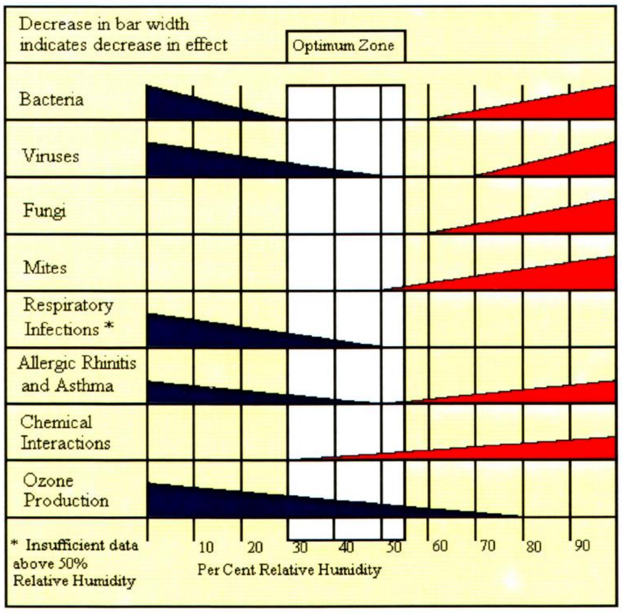


Fig. 1. Impact of relative indoor air humidity on various health and comfort factors /10/.

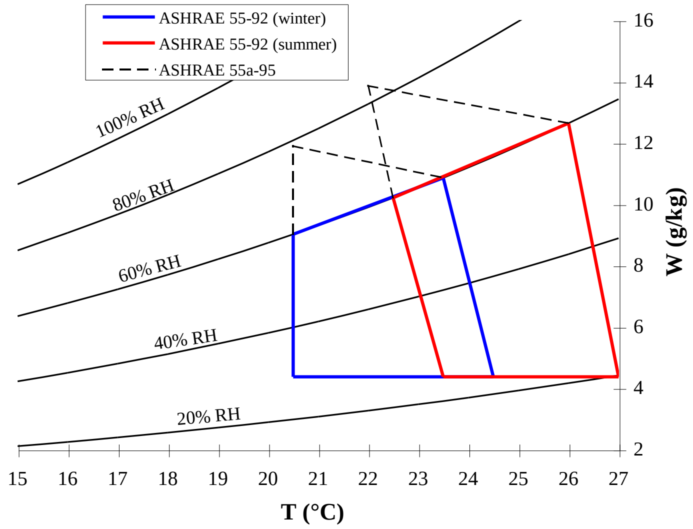


Fig. 2. Summer- and wintertime comfort conditions /11 and 12/.

3.2.2 Tapanila Ekotalo

The first practical indications on the beneficial impact of cellulose fibre insulations on indoor climate were obtained during the Tapanila Ekotalon field surveys back in 2000 (Fig. 3) /1, 5, 6 and 8/. During the finishing stage of eco-designed houses certain tests were performed in order to determine the said impact in real conditions. The results have confirmed the assumptions regarding the ability of open, hygroscopic structures to influence noticeably upon the indoor air humidity rate.

The survey was performed in one sleeping room, where the outer and inner wall as well as the roof structure consisted of a 13 mm plasterboard, construction paper and timber frame filled with cellulose fibre insulation. The outer walls were ventilated and lined with wood. The inner plasterboards were painted with vapour-permeable paint. The floor planks were processed, so their impact on humidity interaction was marginal.

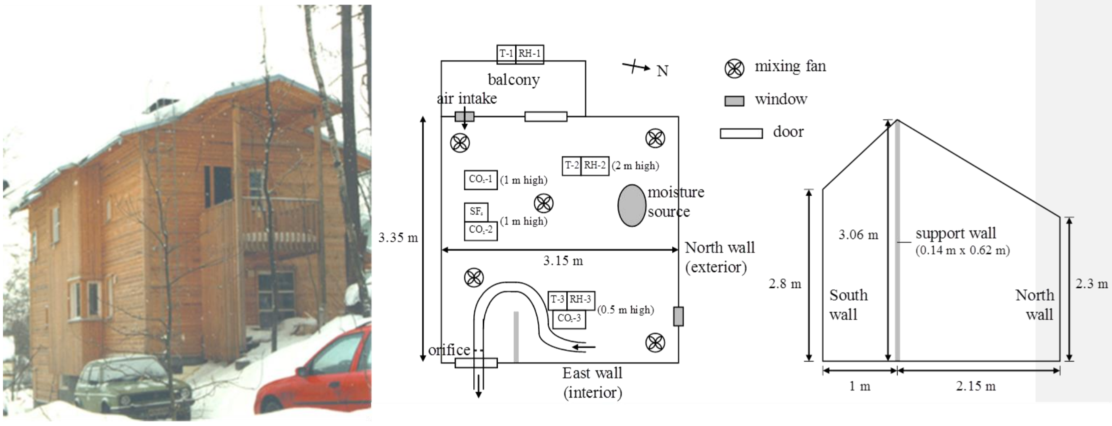


Fig. 3. Tapanila Ekotalo and the tested room dimensions.

In a room of approx. 11 m^2 there was a total of 28 m^2 wall surface insulated with cellulose fibre. During the test, the room ventilation could be set to a desired level and a moisture input equalling two persons (87 g/h) was fed into the room for 8 hours every night. At other times the room was ventilated in the same manner as during load time. The temperature was set to a minimum level of +23 ^{o}C, however it may have grown higher in the measurement period.

During the preparations the room temperature was measured, together with humidity at different ventilation rates, including the mentioned recurring night-time moisture input. This stage reflected a hygroscopically open structure. In the second stage all inner surfaces were covered with a vapour barrier foil, so that the structure's moisture capacity could not alter the room humidity. The entire measurement lasted from 14 to 31th May 1999. The outdoor temperature fluctuated between 0 ^{o}C and +20 ^{o}C (+11 ^{o}C on average).

Błąd! Nie można odnaleźć źródła odwołania. indicates the test periods and the ventilation coefficients used. In the initial stage of 14-24th May, the inner surface of the tested structures was in touch with the indoor air (*No Plastic*) and on 25-31st May the inner surface of the structure was covered with vapour-tight foil (*Plastic*), so that the vapour transmission between the structure and indoor air was obstructed. In addition, the figure includes the measured partial pressures of indoor air during the test time, as well as numerical values of partial pressures calculated on basis of outdoor air conditions, structures, ventilation and exposure to vapour.

The dynamics evident in the numerical results and the calculated partial pressure levels corresponded tightly with the measurement results throughout the most of the analysis period. On basis of the results the phenomena can be observed reliably also in numbers.

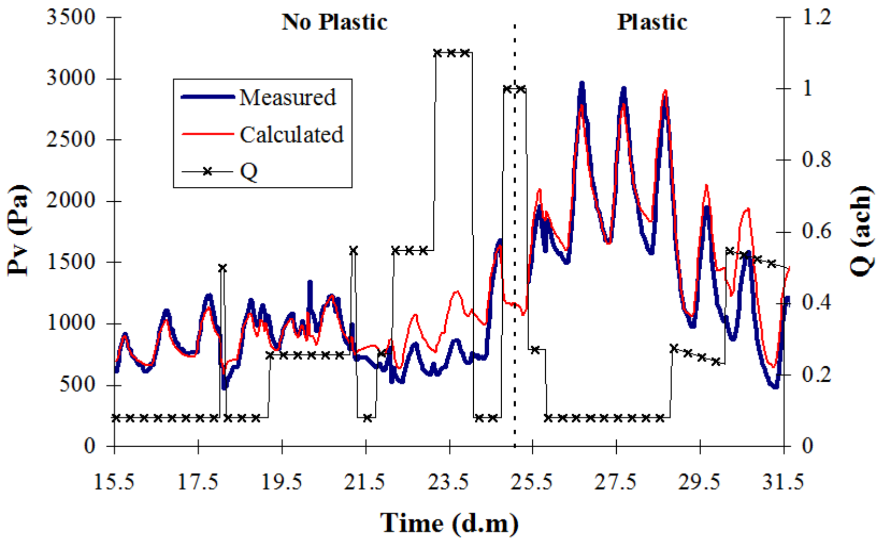


Fig. 4. Air ventilation volumes (Q,ach [1/h]) during the test period. During the No Plastic stage the structures were open to indoor air. During the Plastic stage all structures were covered with vapour-tight foil. In addition, the measured and calculated vapour partial pressures (pv) of indoor air are presented.

The partial vapour pressure level was higher during the second stage, when all structure surfaces were covered with foil. Every night the moisture input caused the vapour partial pressure to grow in the room. During the first stage in case of hygroscopic structures this increase would be much smaller, compared to the tight structures of the second stage. The test periods cannot be compared directly with each other, because the measurements were affected by weather. Still, the level difference between the both stages was clear.

The moisture-buffering effect of the structures can be assessed most accurately by comparing the changes of relative indoor air humidity during 24 hours for different ventilation coefficients (Fig. 5). According to the results, the growth of relative humidity was significantly higher in case of foil-insulated structures, compared to without foil. In the foil-insulated room the relative humidity updated with 0.55 l/h ventilation coefficient grew more than in case of the bare structure without forced ventilation (0 ach). The default value for air leakage was 0.01 1/h. In this case the impact of hygroscopic structures on the relative indoor air humidity was higher than with the typical ventilation coefficient of 0.5 1/h.

Without the forced ventilation (estimated air leakage 0.1 l/h), the maximum fluctuation of relative humidity in case of foil-insulated structures was 32 % RH, whereas in case of bare structure - half of it, that is 16% RH.

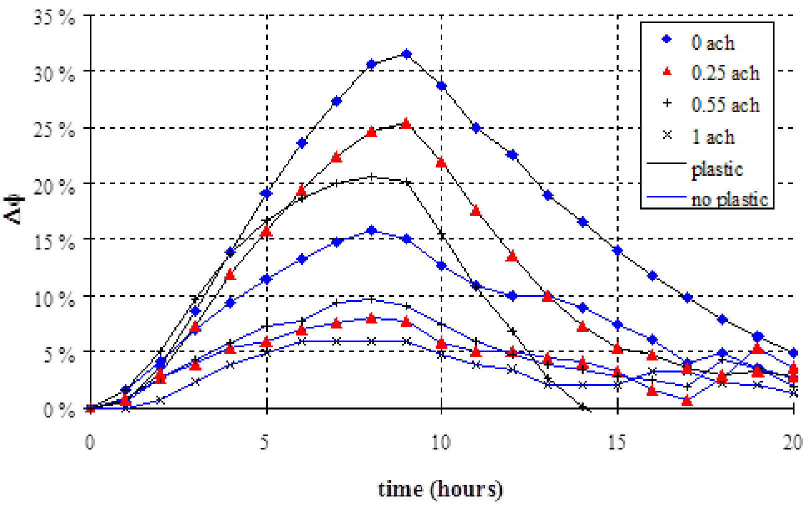


Fig. 5. The increase of relative humidity in ambient air at night time, adjusted with different ventilation coefficients (0, 0.25, 0.5 and 1.0 1/h ach), both with plasterboard (no plastic) and vapour barrier (plastic).

On basis of measurements performed in field tests it is evident that the hygroscopic mass within the structure bears great influence on the indoor air humidity conditions. During the time of high vapour production, the structure can bind moisture, whereupon the relative indoor air climate remains more balanced and the extreme uncomfortable conditions are minimised. The moisture capacity of the plasterboard, used as the finishing element of the test structure, is relatively small, however upon being coated with permeable layers it works as a good transmitter of vapour. In this case the material layers behind the plasterboard - airtight paper, cellulose fibre insulation and timberframe - may be involved in the vapour interaction with indoor air.

3.2.3 Calculation analyses

In a broad research based on numerical simulation /2, 3, 4 and 7/ the operation of a room corresponding with the Tapanila Ekotalo room was reflected: In a sleeping room there are two persons and the ventilation is compliant with the regulations. By means of calculations, the impact of various structures and climate conditions on the indoor air humidity levels were analysed during the year.

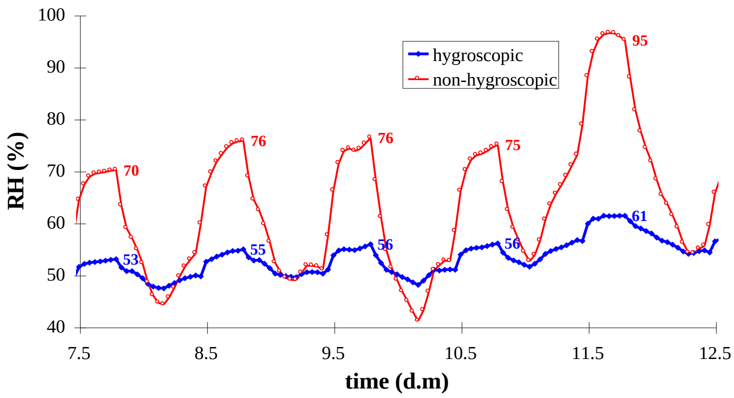
Table 1 presents certain structure cases used in the calculation. As a reference situation, structures were almost vapour-tight on their inner surface.

Table 1. Structures used in the comparison of calculated surface resistance.

Structure	Inner surface finish	Inner finishing board (porous fibreboard)		Air barrier	Thermal insulation
	Vapour permeability	Moisture capacity	Vapour permeability	Vapour permeability	Moisture capacity
Hygroscopic	High (vapour-permeable)	High	High	High (paper)	High (cellulose fibre)
Non-hygroscopic	Low (vapour-resistant paint)	High	High	High (paper)	High (cellulose fibre)

The analyses have been performed in varying European conditions. The indoor temperature was adjusted according to the regional practice. The room ventilation was set to a fixed level of 0.5 1/h. In the next point, certain excerpts from the results are presented.

Fig. 6 /2/ indicates the relative humidity values during a selected mild period in Belgium and a cold period in Finland in terms of hygroscopicity of different structures. The examples reflect the effective damping of the fluctuation of the indoor air relative humidity during dynamically changing load. In mild weather conditions the indoor air relative humidity tended to grow 30-35% RH for non-hygroscopic structures, whereas in case of hygroscopic structures it remained on a level of 5-8% RH. In cold weather conditions the growth figures amounted to 20-30 % RH and 5-10 % RH, respectively.



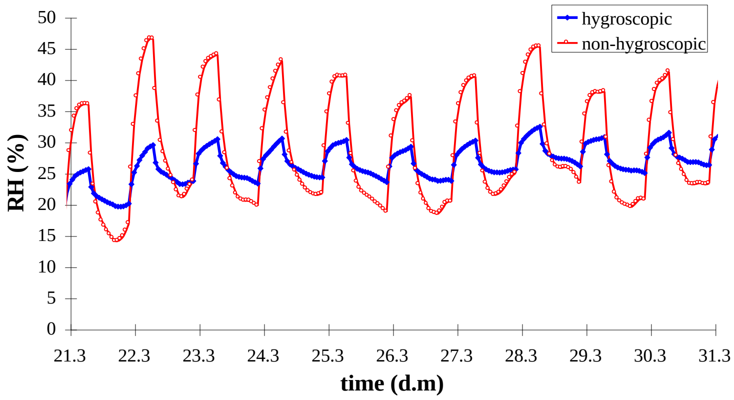
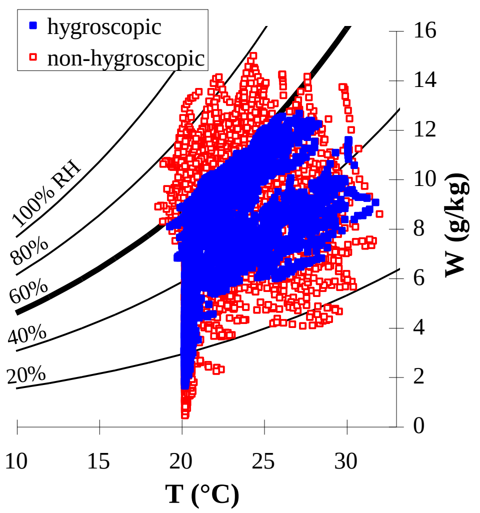


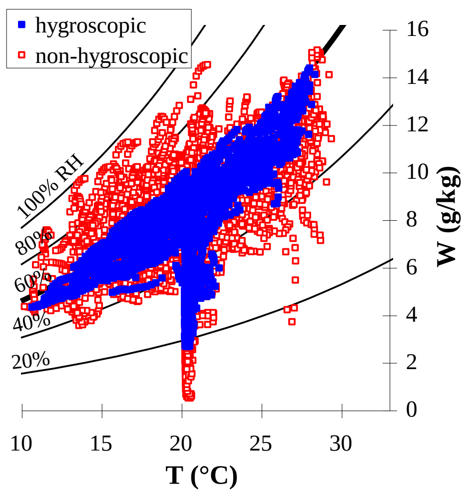
Fig. 6. Relative humidity values during a selected mild period in Belgium (above) and a cold period in Finland (below) with a hygroscopic and non-hygroscopic structure /2/.

Fig. 7 indicates the hour-based calculated temperature and relative humidity values in four different climates during the year. In all cases, in terms of non-hygroscopic structures, there occurrence of extreme values of relative humidity (very dry or very damp air) was more frequent than in case of hygroscopic structures. The extreme relations were typically outside the comfort area or on its borders, so their minimisation stands for an improvement of the experienced air quality and comfort.

Helsinki

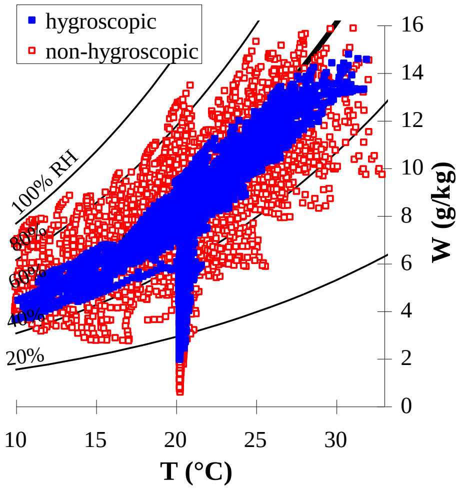


Saint Hubert, Belgium



Holzkirchen, Germany

Trapani, Italy



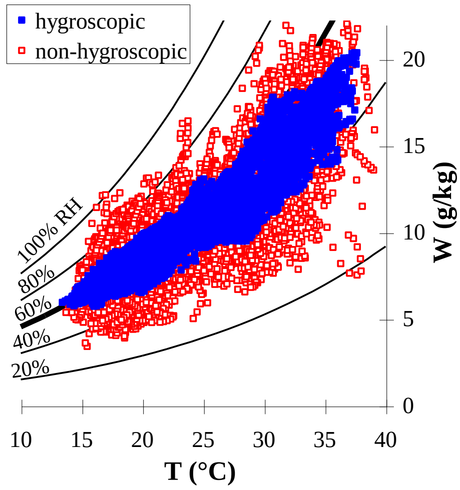


Fig. 7. The hour-specific temperature and relative humidity values in the test room were calculated for the weather conditions of Finland, Belgium, Germany and Italy. The minimum temperatures vary due to the typical settings and heating devices used in different countries /2/.

3.2.4 Moisture capacity measurement method

Within the Scandinavian NORDTEST project (2004-2005) the *MBV* value (*Moisture Buffer Value*) was defined as the buffer impact of building materials on humidity /14-16/. In this connection, also the empirical test method of the MBV value was presented. Before that the hygroscopic functionality could be determined on basis of material properties or as input assumptions in simulations. When the moisture buffering effect can be represented with a single value, the comparison of various cases is much easier.

In the presented research environment, the test piece was kept for 8 hours in a fixed high humidity and for 16 hours in low relative humidity. The test temperature was fixed at +23 ^{o}C. Before the test the humidity of test pieces was balanced in fixed conditions (approx. 50 % RH and approx. 23 °C). The typical relative humidity values used in the tests are 75% RH for a period of 8 h vapour input period and 33% RH for the 16 h drying period. The cycles were repeated and the test piece weight was constantly supervised. When the weight difference between two consecutive cycles reaches a maximum of 5 %, the test is interrupted (Fig. 8).

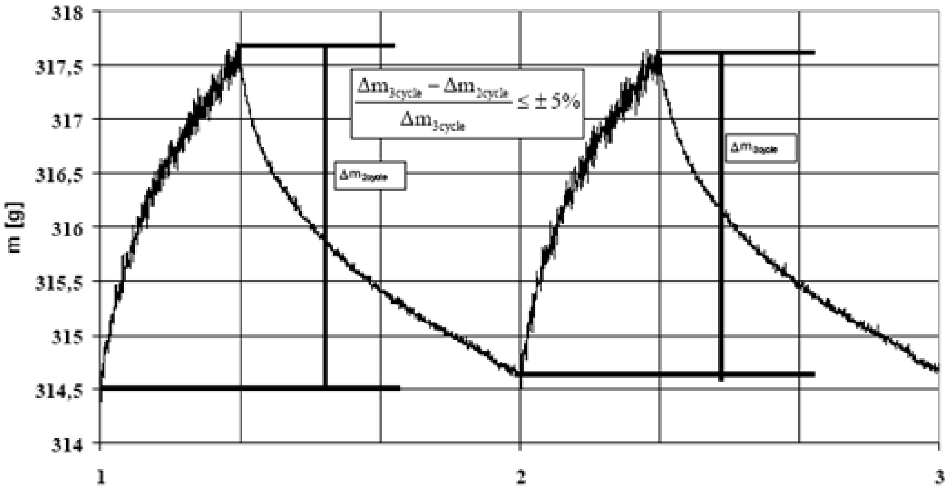


Fig. 8. The typical test piece weight change in cycles and test end criterion.

MBV value is calculated on basis of the last cycle measurement results and its unit is g/m2ΔRH. This figure can be counted with formula 1

$$MBV = \frac{m_1 - m_0}{(RH_2 - RH_1)\cdot A}, \qquad (1)$$

where m_0 [g] is the test piece weight prior to the last moisturising period, m_1 [g] is the test piece weight at the end of the given moisturising period, RH_1 is the lower relative humidity [%], RH_2 is the higher relative humidity [%] and A is the effective test piece surface, which is in contact with the indoor air.

Fig. 9 indicates the MBV value of test equipment. The test piece is constantly weighed in the central chamber. In the adjacent chamber, a permanent humidity environment is maintained with salt solutions. By means of valve and blower controls it is possible to move the air to the test chamber from the desired space and therefore enforce very sharp cyclical fluctuation of air humidity.

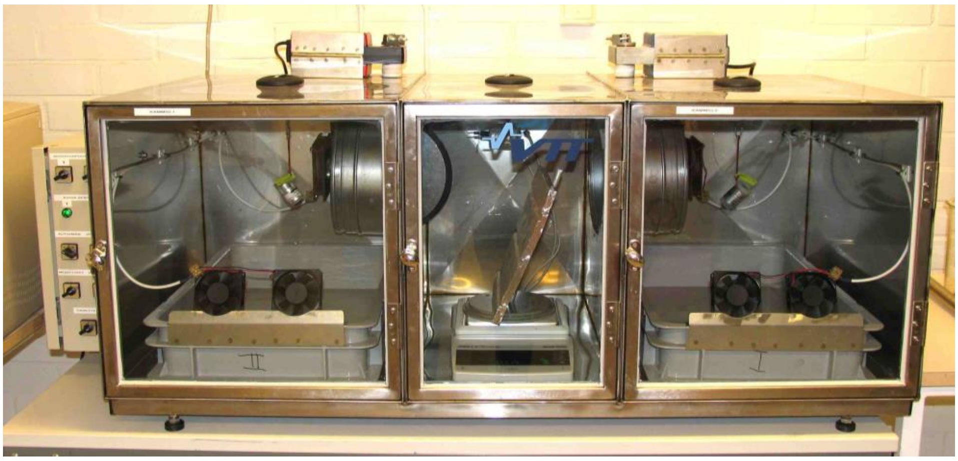


Fig. 9. Equipment used by VTT for the defining of the moisture buffer capacity /16/.

Fig. 10 indicates the typical measurement data of the MBV tests and Fig. 11 indicates moisture capacity values defined empirically for certain materials. It is worth noting that the values refer to non-coated test pieces of material batches and do not describe the moisture buffering in a structural application.

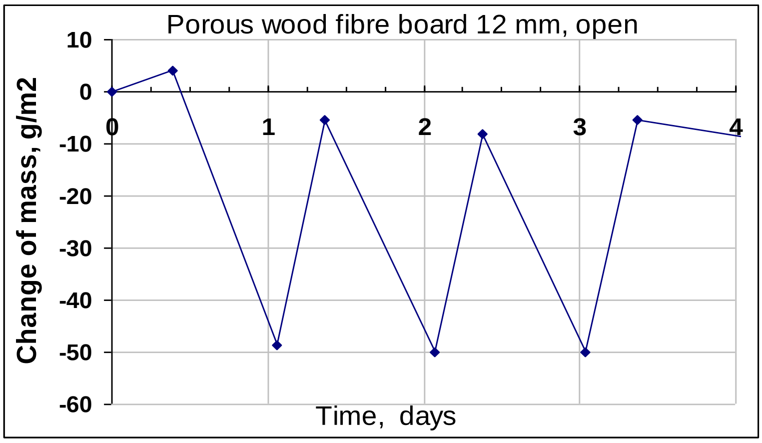


Fig. 10. Example of moisture fluctuation in a porous fibreboard during one cycle.

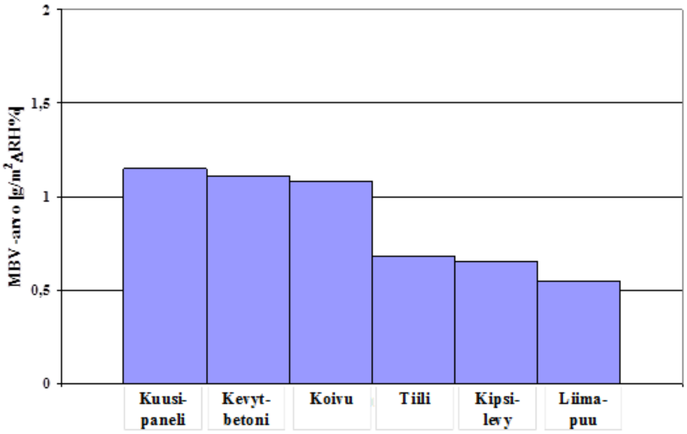


Fig. 11. MBV values reflecting the vapour capacity of different materials /16/.

The developed method enables the presentation of the vapour capacity of a certain material or structure component by means of a single comparable parameter, so as to facilitate the evaluation of vapour capacity. This method, however, has been used quite rarely, and the MBV is not indicated for materials or structures. The reason for this may be the additional effort associated with the separate testing method and the fact that the vapour movements can be evaluated by means of calculations based on humidity properties of certain materials in a complex structure. Especially the processing of the inner surface and its coats influence significantly upon the moisture flows between the structure and indoor air, while the different variations of a complex structure cause great discrepancies of the MBV value.

4. Vapour-related functionality in exemplary structures

4.1 Objectives and criteria

The aim of the research was to determine the vapour-related functionality of selected exemplary dry room structures in the Finnish climate. The main criteria included moisture accumulation and quantitative analysis of mould growth. The mould growth analysis was based on a model developed by VTT as an analytical tool of calculation results.

4.2 Test structures

Three structures were analysed, including one wall structure and two roof structures (Fig. 12, Fig. 13 and Fig. 14). The air/moisture barrier properties of the structures, thermal insulation material and thickness, as well as roof air barriers were analysed subject to different estimations, in order to ensure a possibly wide scope of applications. Typically, a structure with vapour barrier and in some cases a structure with a vapour-tight inner surface was used as reference.

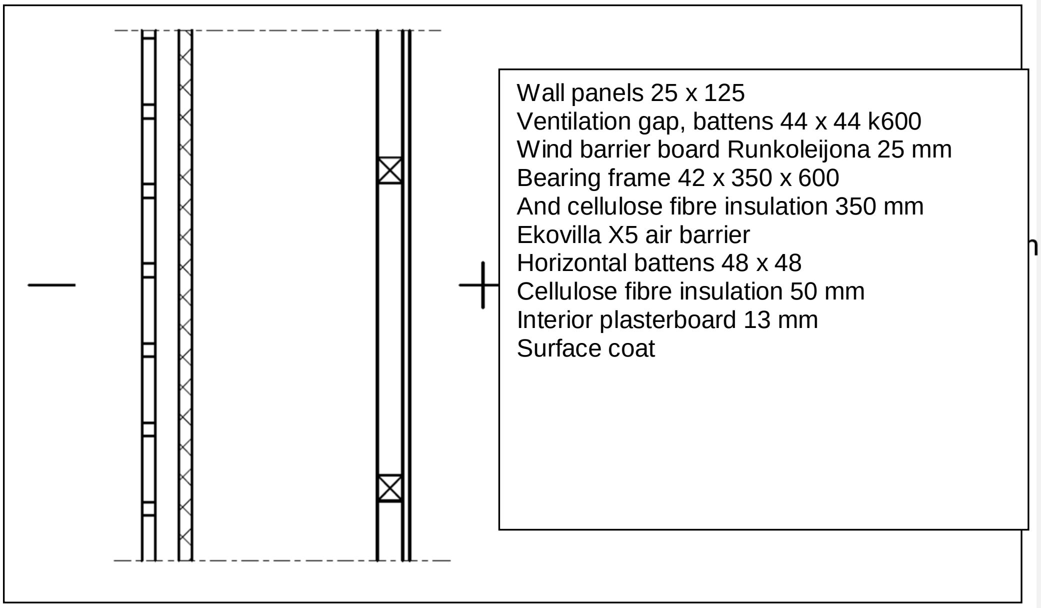
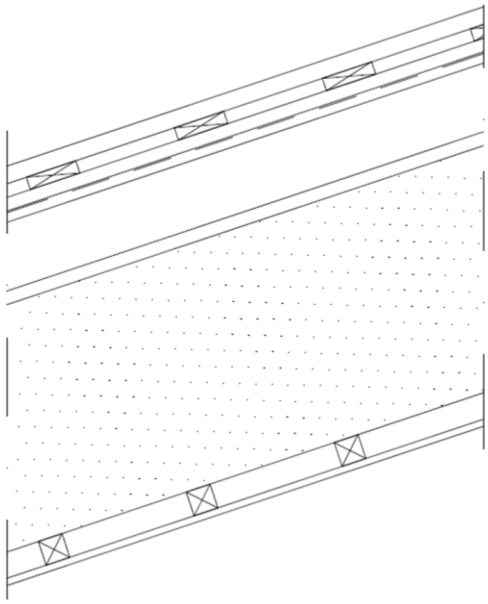
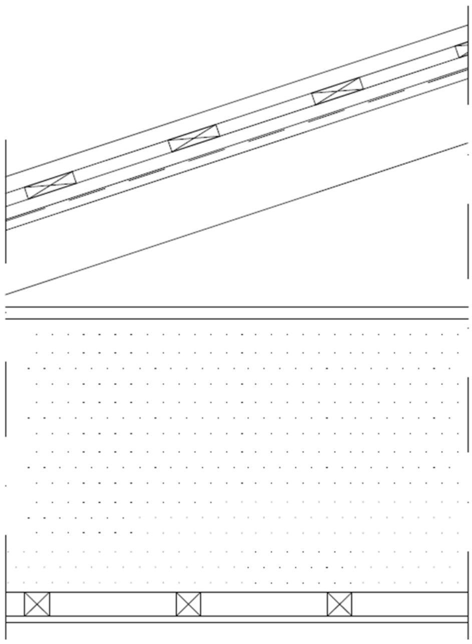


Fig. 12. Wall structure used in the analysis. Different airtight layers have been used in the analysis: X5, Intello and OSB board. The reference structure included PE vapour barrier. Also the functionality of a structure with 175 mm insulation was examined.



Metal sheet
Planks 25 mm
Battens 25x50 k900 (ventilation gap)
Membrane
Batten 20 x 45 k900
Roof truss 600 mm k900
In the roof truss:
- Ventilation gap > 100 mm
- Wind barrier board Runkoleijona 25 mm
- Cellulose fibre insulation 450 mm
Air barrier (X5)
Battens 48 x 48 k300 (air gap)
Interior plasterboard 13 mm
Surface coat

Fig. 13. YP1: slanted, ventilated roof insulation structure. Depending on the situation, either X5 product or vapour-tight foil is used in the analysis.



Metal sheet
Planks 25 mm
Battens 25x50 k900 (ventilation gap)
Membrane
Batten 20 x 45 k900
Roof truss 600 mm k900
In the roof truss:
- Ventilation gap > 100 mm-
- Wind barrier board Runkoleijona 25 mm
- Cellulose fibre insulation 450 mm
Air barrier (X5)
Battens 48 x 48 k300 (air gap)
Interior plasterboard 13 mm
Surface coat

Fig. 14. YP2: Horizontal insulation in a ventilated roof. Air barrier: Runkoleijona fibreboard or no air barrier. Depending on the situation, either Intello X5 product or vapour-tight foil was used in the analysis.

4.3 Analytical methods

During the analysis, the WUFI 5.3 simulation software /17/ was used for the 1-d analysis of cross-sections. The software resolves the distribution of temperature and humidity of the cross section based on hour-specific extreme conditions, as well as considering the thermal and moisture properties of material layers.

Mould growth is the first symptom caused by the extensive moisture in the building structure. In the subsequent analysis of the calculation results the mould growth risk was analysed in the critical construction elements. Mould growth was evaluated with the model developed by VTT which has been updated with the mould vulnerability indicator of the different materials /18 – 24/.

4.3.1 Mould growth supervision

The mould growth calculation model relied on the visual classification of mould propagation on the material surface (Table 2). On basis of numerous tests, the mould growth was determined with a calculation model computing the mould indicator value dynamically in changing conditions. On basis of surface conditions selected as critical it was possible to calculate the mould growth indicators (0, 6) in different cases.

The mould indicator value 1 refers to the initial mould growth detectable with microscope, while level 3 refers to the first macroscopic detection or over 50% coverage of microscopic surface view. The critical maximum value of inner surface and elements exposed directly to indoor air is regarded to be level 1, which in practice means that no mould growth is allowed. The limit for layers adjacent to outer surface is often level 3, because the outdoor air conditions lead acutely to a mild mould growth potential in these areas of the structure. As they are in no direct contact with the indoor air, they do not cause an adverse contamination risk more than the normal outdoor air inflow.

It is worth noting that the mould growth does not mean the damaging of structures e.g. with regard to their solidity. The decay affecting the solidity may increase drastically at higher humidity levels and in general it is equal with being soaked with water. The damage inflicted by mould growth to the elements adjacent to outer surface is mainly of aesthetic nature. Mould indicator level 3 corresponds with the first visible filaments which normally may appear in the parts bordering with the air gap.

Table 2. Definitions of different levels of mould growth progress detection used as the basis of the VTT mould growth model.

Mould growth indicator	Observed mould growth	Remarks
0	No growth	Clean surface
1	Locally commencing growth	Few filaments
2	Detectable with microscope	Colony
3	Macroscopically detectable commencing growth	Spores, colony coverage below 10 % of the surface
4	Macroscopically detectable growth, mild	Colony coverage 10-50% of the surface
5	Macroscopically detectable growth, locally abundant	Colony coverage over 50% of the surface
6	Intensive growth	Abundant growth, colony coverage almost 100%

Mould growth depends on the mould vulnerability of the substrate. The materials are classified in four different groups according to the mould growth vulnerability (Table 3).

Table 3. Mould growth vulnerability classes of certain construction materials /23 and 24/.

Mould growth vulnerability class	**Materials**
Very sensitive	Non-machined, pine wood abundant with nutrients
Sensitive	Paper-coated products and membranes, wood-based boards, grinded pine wood
Medium resistant	Cement-based materials, plastic-based materials, mineral wools, polyester wool
Endurable	Glass and metal materials, products including active protective agents

The most sensitive level refers to a surface analogical to non-treated pine wood surface (*very sensitive*).

The next vulnerability class (*sensitive*) corresponds with a typical product with a wooden or paper surface, grinded pine wood or plasterboard.

The next class (*medium resistant*) refers to cement and plastic-coated materials and mineral wool products.

Mould-resistant level 4 (*resistant*) contains glass, metal and other similar materials, which have been treated with fungicides.

The calculated mould indicator is reduced during dry and cold periods, in order to reflect the mould regress. As a corrective regress factor of the mould growth indicator, a coefficient of 0.25 was used. This describes the reduction of mould growth speed in resistant conditions compared to the sensitive wood indicator, so that the used value is more reliable.

4.4 Climate data used in the calculation and vapour exposures

The calculation was performed on basis of weather records of 2007 taken in Vantaa, Finland, which were intended as dimensional data of the humidity-related functionality of non-ventilated structures. In the analysis, the outdoor air conditions (temperature, relative humidity, rain, wind and solar radiation data) are specified on an hourly basis. The weather conditions in a multi-year analysis change on an annual basis. The analysis was performed case-specifically for 3-6 year periods.

The indoor air conditions are defined according to EN 15026 as relevant for normal vapour exposures. In this respect, indoor air is constant +20 °C as long as outdoor air is below +10 °C. When the outdoor air temperature changes from +10 °C to +20 °C, the indoor air temperature grows in a linear manner from +20 °C to +25 °C. In case of higher outdoor temperature, indoor air is constant +25 °C.

When the outdoor temperature falls below -10 °C, the relative indoor air humidity is 30 % RH. The indoor air relative humidity growth in a linear manner from this point to RH 60 % along the increase of outdoor temperature from -10 °C to +20 °C. The maximum value of relative humidity is 60 % RH. The presented vapour exposure reflects the humidity of dry rooms and additionally includes a certain degree of certainty.

The assumed initial humidity of all material layers is a balancing humidity of 80% RH, unless defined case-specifically otherwise.

4.5 Material properties

Table 4 indicates the vapour permeability properties used in the calculation /17/.

Table 4. Material layers and their vapour permeability properties.

Material layer	Layer thickness, mm	Density, kg/m^3	Vapour diffusion resistance coefficient μ
Cellulose fibre insulation	350/175/48	40	2.3
Cellulose fibre insulation	48	70, 120	2.3
Mineral wool	350 / 48	20	1,3
OSB	20	630	650 - 100 f (RH = 0, 100 %)
X5 air barrier	1	-	700 (S_d = 0.7 m)
Intello vapour barrier	1	-	26000 - 250 f (RH = 0, 100 %)
Leijona wind barrier board	24	300	12.5 – 3.5 f (RH = 0, 100 %)
Indoor finishing panel	12.5	625	8.3 – 2.6 f (RH = 0, 100 %)

The diffusion resistance of airtight paper X5 /25/ is S_d = 0.7 m, which corresponds with construction paper of high vapour permeability. S_d – this value indicates how thick air gap equals the product's vapour permeability resistance.

The diffusion resistance of the intello vapour barrier changes along with relative air humidity. In a dry room the vapour resistance is on the level of vapour barrier (S_d > 10 m), while on the humid side it is lower than the one of construction paper.

OSB, oriented strand board, is a construction board made of glued wood chips. Its vapour resistance may vary depending on the product. In addition, the resistance depends on the moisture level, as the case with wood products in general.

The densities (70 kg/m^3 and 120 kg/m^3) exceeding the density of typical insulation products (approx. 40 kg/m^3) do not correspond directly with the existing products, however these densities were also analysed in order to clarify the impact of changed vapour capacity on moisture flows and balancing. The assumed diffusion resistance of these products was 40 kg/m^3.

4.6 Wall structures

4.6.1 Study cases

In Table 5 the test wall structures are presented. In the course of research, various wind barrier, thermal insulation, as well as air/vapour barrier materials were used. In all cases the vapour resistance of the interior panel coat was S_d = 0.02m which corresponds very well with highly permeable clay paint. The small inner surface moisture resistance increases the analytical accuracy of humidity-related functionality in the Finnish climate.

Table 5. Test wall structure cases. Wind barrier: either 24 mm porous fibreboard or 12.5 mm plasterboard.

Code	Wind barrier board	Thermal insulation	Vapour/ air barrier	Thermal insulation, inside 48 space	Rain inside the structure
E	24 mm hk	350 mm cellulose fibre	X5	cellulose fibre	No
Eg	12.5 mm plasterboard	350 mm cellulose fibre	X5	cellulose fibre	No
Eint	24 mm hk	350 mm cellulose fibre	Intello	cellulose fibre	No
Eosb	24 mm hk	350 mm cellulose fibre	20 mm osb	cellulose fibre	No
mw	24 mm hk	350 mm mineral wool	HS	mineral wool	No
mwi	24 mm hk	350 mm mineral wool	HS	air gap	No
R2	24 mm hk	350 mm closed pore	Al-surface	closed cell	No
E%	24 mm hk	350 mm cellulose fibre	X5	cellulose fibre	1 % diagonal rain
E,int%	24 mm hk	350 mm cellulose fibre	Intello	cellulose fibre	1 % diagonal rain
En%	24 mm hk	175 mm cellulose fibre	X5	cellulose fibre	1 % diagonal rain
Eg%	12.5 mm plasterboard	350 mm cellulose fibre	X5	cellulose fibre	1 % diagonal rain
Egn%	12.5 mm plasterboard	175 mm cellulose fibre	X5	cellulose fibre	1 % diagonal rain
Eosb	24 mm hk	350 mm cellulose fibre	20 mm osb	cellulose fibre	1 % diagonal rain
mw%	24 mm hk	350 mm mineral wool	HS	mineral wool	1 % diagonal rain

One the reference structures was insulated with a vapour barrier and mineral wool, inside of which there was a 48 mm insulation cavity filled with either mineral wool (mw) or air gap (mwi). In the second reference structure, a non-porous, non-hygroscopic insulation material was used, coated with aluminum membrane (R2).

The thermal insulations of reference structures did not originate directly from existing products. The thermal conductivity of all thermal insulations is always 0.039 W/mK. In this way the differences of thermal functionality have not affected the differences in terms of humidity-related functionality. Furthermore, the differences in heat flows have been mainly based on moisture phase change, and not other differences in material properties.

4.6.2 Results of wall structure functionality

The critical points of the structure in terms of humidity-related functionality are the both surfaces of the wind barrier and especially its inner surface, the humidity of which can be increased by the moisture passing from the indoors. The outer surface of wind barrier is mostly impacted by the air gap conditions.

Normal moisture input situation

Fig. 15 indicates the mould indicator results imported from calculatory analysis for the inner surface of the wind barrier, where the structure is protected against water penetration.

When plasterboard is used as a wind barrier, during the first year the vapour moving outwards the structure has caused a slight increase of the indicator on the inner surface of wind barrier, when the most sensitive *very sensitive* material class was applied. The calculatory indicator reached 1, which does not indicate any real mould growth risk in teh structure. The momentary value on the first microscopically detectable level inside the structure does not cause a growth risk. In other structures the mould growth indicator was very low in the initial drying phase (<0.15).

The mould growth indicators for wind barrier outer surface remained almost zero in these cases, and these results are not visually presented. On basis of the results it can be concluded that there is no mould growth risk in normal vapour exposure conditions.

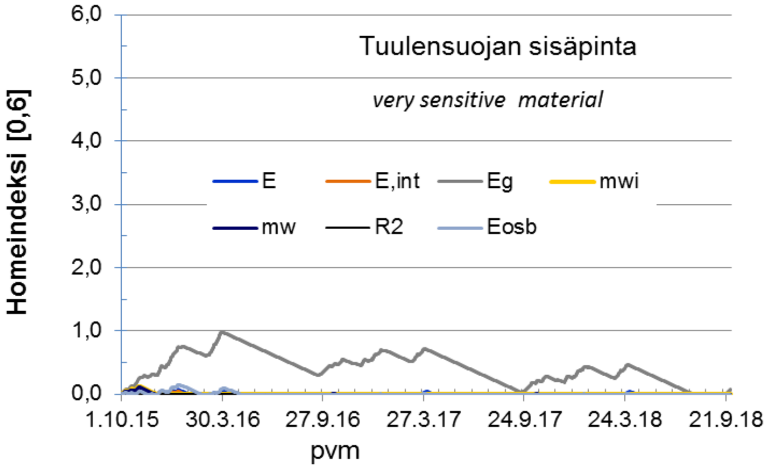


Fig. 15. The mould growth indicator of the wind barrier inner surface has remained on a safe level in all cases. Mould vulnerability of the material: Very sensitive.

Rainwater penetration into the structure

The penetration of rainwater into the structure reflects the functioning of the structure in case of abnormal exposure to humidity. In such calculated scenarios it has been assumed that 1% of diagonal rain has penetrated via the wind barrier to the outer 50 mm thermal insulation layer as water and has caused moisture exposure inside the structure. The situation reflects the improper functioning of the structure and its purpose is to provide a view of the structure's durability under exceptional exposure.

Fig. 16, Fig. 17 and Fig. 18.

The mould growth indicator of wind barrier outer surface was below limit 1 reflecting the microscopic vegetation in all analysed structures (Fig. 16).

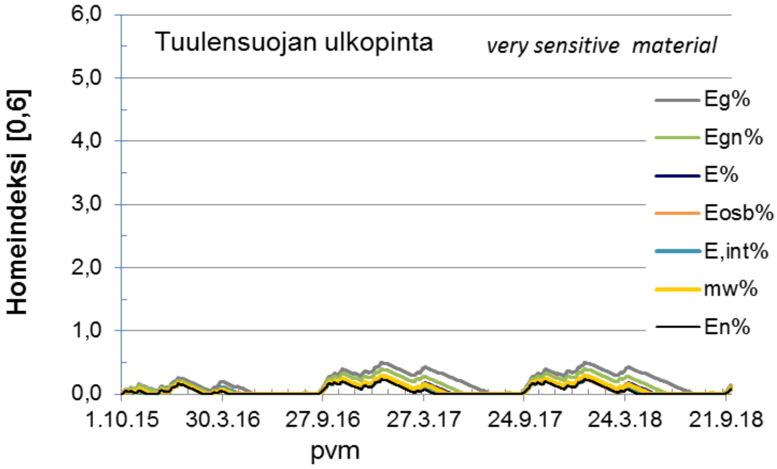


Fig. 16. Mould growth indicator of the outer surface of wind barrier, in case of penetration of 1% of rainwater into the thermal insulation layer. Mould vulnerability of the material: Very sensitive.

Mould growth was visible on the inner surface of the wind barrier, where excessive moisture content was accumulated on its way outwards.

With a *sensitive* class (Fig. 17) the mould growth indicator of plasterboard structures (Eg% and 175 mm insulation Egn%) reached the highest level in the calculation. In these cases the development of the mould growth indicator during a six year period has remained on level 2. This is still an acceptable result for the layer near to the structure's outer surface, however, the growth of indicator value indicates an increased risk.

A structure including 24 mm Leijona wind barrier board, cellulose fibre insulation and X5 airtight membrane (E%), calculatory mould growth level remained at approx. 1 and no additional growth was detected. On basis of these results the structure is secure.

The mould growth indicator for vapour-tight structure (mw%), Intello vapour-tight structure with variable vapour permeability (E,int%) and 175 mm cellulose fibre insulation structure with Leijona wind barrier and X5 air barrier (En%) was below that level. Due to the high humidity of OSB airtight structure (initial humidity of OSB), the mould growth indicator was 1,0 in the first year, but subsequently it ceased to grow. The OSB structure was also secure in terms of mould growth on the inner wind barrier surface, as by default it was defined as a *sensitive* material.

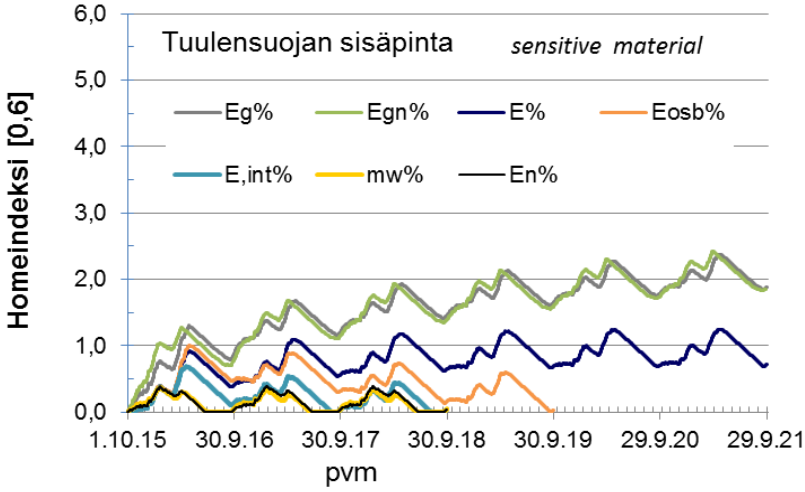


Fig. 17. Mould growth indicator of the inner surface of wind barrier, in case of penetration of 1% of rainwater into the thermal insulation layer. Mould vulnerability of the material: Sensitive.

Fig. 18 indicates the mould growth indicator results for the inner surface of the wind barrier, as for *very sensitive* material. The situation, where a significant amount of water penetrates into the structure and the inner surface material of the wind barrier has a *very sensitive* class, it leads to moisture-related risks. The risk is visible in the conditions pertaining to the inner surface of wind barrier.

According to the results, good vapour permeability in this situation generates extra moisture input in well insulated structures and their mould growth indicator grew within three years to a level of 4-5. The highest results where detected for plasterboards, whereas a porous fibreboard (E%) only showed slight vegetation marks.

If indicator value 3.0 is regarded as a limit for surfaces adjacent to outdoor air, also the OSB air barrier and Intello vapour barrier together with the porous fibreboard have jointly lead to the far exceeding of this value during the first three years.

In this case the mould growth on vapour-tight mineral wool structure (mw%) and 175 mm cellulose insulation (En%) structure was the slowest. Within a six-year research period the indicator remained slightly below 3, however there was also still a modest annual progression. The values between 2 and 3 reflect the increased mould growth risk also in outer layers, whereas the functioning of the structure does not appear to be completely safe in the research conditions.

In this case the mould growth in a non-hygroscopic and vapour-tight structure was slower than in an analogical structure with a hygroscopic insulation and vapour-permeable air barrier. A certain mould risk is involved in all of the cases, however the slowest progress enables taking of countermeasures before excessive vegetation.

Apart from additional moisture input from indoor air, the growth is also regulated by the maintenance of humidity conditions on the border surface. In this case a thin insulation layer (En%) and heat loss exceeding good insulation thickness have stimulated the drying of the critical border surface and slowed down the growth of mould which was on the same level as in the structure with vapour barrier and a thicker non-hygroscopic thermal insulation layer (mw%). Thinner insulation has not provided a sufficient protection against mould growth risk, either. With plasterboard used as wind barrier, insulation thickness did not influence the mould growth. This is caused by the plasterboard vapour permeability and the fact that on its surface there is no such partial pressure difference like in the case of a thicker and more strongly insulating porous fibreboard. The certainty of moisture-related functionality does not rely on the insulation thickness, but the functioning of all the structural layers as a whole.

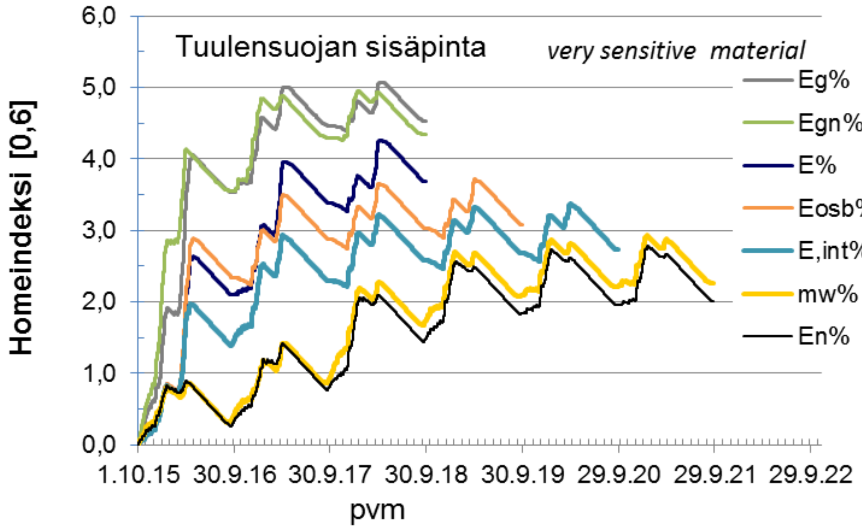


Fig. 18. Mould growth indicator of the inner surface of wind barrier, in case of penetration of 1% of rainwater into the thermal insulation layer. Mould vulnerability of the material: Very sensitive.

Rainwater penetration into the structure always involves a certain fault. The examined cases indicate the vulnerability of the specific structures to the problems of moisture-related functionality. In this respect, the impact of vapour permeability, additional exposure caused by initial humidity of indoor air and material layers, hygroscopic materials and insulation thickness. None of the analysed structures was completely safe, if the materials on the inner surface of the wind barrier were classified as *Very sensitive*.

4.6.3 Potential condensation in the wall structure in the summertime

The research objective was to examine the summertime (1st May - 30th Oct) humidity on the different sides of the vapour and air barrier. Rakenteena oli aiemmassa toimivuustarkastelussa käytetty tuuletettu ja puuverhottu seinärakenne (Fig. 12), jossa on 24 mm tuulensuojalevy (huokoinen kuitulevy), 350 mm lämmöneriste, höyryn/ilmasulku, 48 mm sisäpuolinen eristekerros ja sisäverhouksena 13 mm kipsilevy.

The structure in the Finnish climate conditions and its indoor temperature was a constant +20 °C which corresponds with artificial cooling. The surface facing South was prone to diagonal rainfall and solar radiation (absorption coefficient 0.80, dark wooden surface). In addition, 1% of rainwater penetrated via the wind barrier into the external 50 mm insulation layer, and added exposure to outdoor moisture. The analysis conditions had a high degree of accuracy, in other words they reflected the possible moisture accumulation in the critical structural points. Critical place, outer surface of air/vapour barrier.

Fig. 19 indicates the relative humidity values on the both sides of the air/vapour barrier in two different structures: Case E, with cellulose insulation and X5 air barrier, as well as ref,hs, with mineral wool and vapour barrier.

The relative humidity outside the vapour barrier grew in the research conditions shortly above 80 % RH (maximum of 85 % RH), and in case of the vapour-permeable air barrier it reached a maximum of 73 %. There has been no water was liquefied in the structure. moisture-related risks in Finnish climate were not detected in either of the structures.

If the outdoor conditions were significantly warmer (or indoor air was cooler) and moisture would penetrate from outside, the situation could change. Typically, a structure transmitting vapour in both directions improves the functional safety compared to a vapour-tight structure. The humidity levels of hygroscopic structures open to diffusion in both directions are more balanced in different exposure situations than in case of non-hygroscopic and vapour-tight structures. The ensuring of functionality in different climates and exposure conditions requires further surveys.

Conduction flows were more balanced than in case of a vapour-tight structure (Fig. 20). Moisture transfer and its phase changes balance the heat flow peaks.

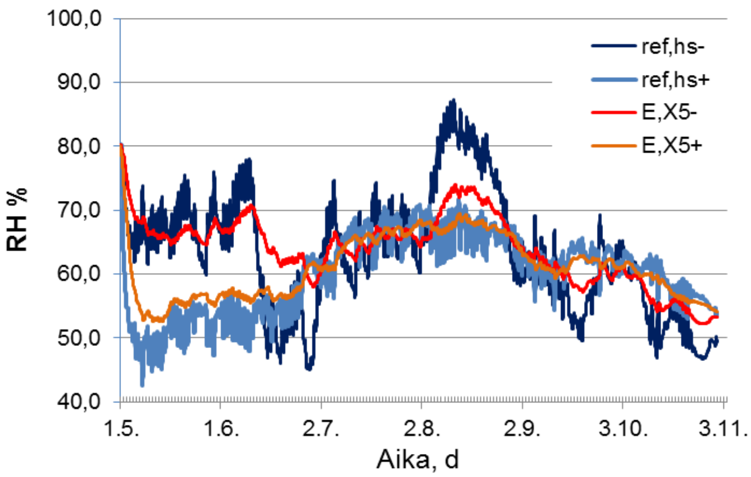


Fig. 19. Relative humidity values on the both sides of the vapour/air barrier.

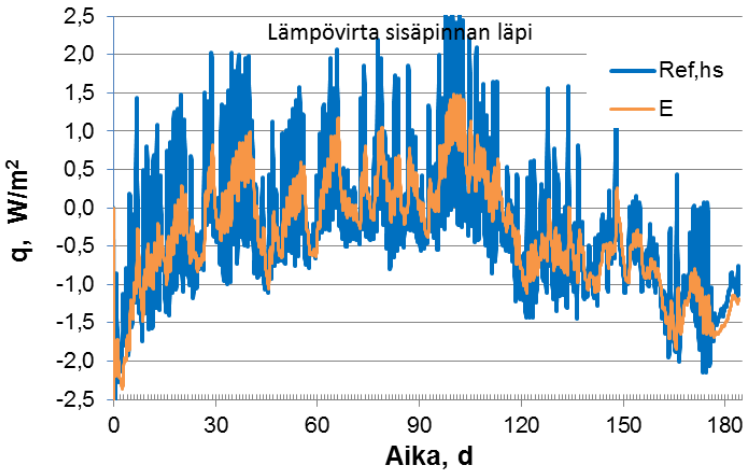


Fig. 20. Conduction heat currents through the structure's inner surface during 1st May – 30th Oct.

4.6.4 Summary of the humidity-related functionality of wall structures

Normal exposure conditions of dry indoor air and outdoor air

As a summary of the research on humidity-related functionality, it can be stated that hygroscopic structures are safe with regard to moisture economics in normal, dry residential rooms, provided that the outdoor air exposure corresponds to structures that are protected against rainwater and ventilated. In this case, the materials of the specific layers can correspond to the highest class of 'very sensitive' at the most. There were no significant differences between non-hygroscopic structures or vapour permeability of different air barriers.

The external surface of the wind barrier represents the conditions of the ventilation gap, and no conditions stimulating mould growth were detected therein during any of the analysed cases.

In the case of the plasterboard air barrier, the mould growth indicator reached 1 on the inner surface of the air barrier during the drying period of the initial moisture and with a *very sensitive* material in terms of mould sensitivity. This cannot be regarded as a risk with regard to the mould exposure of indoor air or the structure.

Additional exposure caused by rainwater penetration

The assumption of moisture penetration (1% of diagonal rainfall amount) behind the air barrier into the insulation reflects an exceptional situation.

The mould risk was not visible on the outer surface of the air barrier in any of the structures. The air barrier board has blocked moisture egression, so that the outer surface remained in safe conditions, but correspondingly the humidity of the inner surface grew due to the penetrating rainwater.

The inner surface of the air barrier was critical for the humidity-related functioning of the analysed wall structures. When 1% of diagonal rainfall penetration behind the air barrier into the insulation was assumed, it led to a mould risk in all structures, provided that the material was 'very sensitive'.

In the case of rainwater penetration into the structure, a slight additional exposure is visible in the results. The slowest mould growth occurred in the structure with a moisture barrier, as well as in the structure insulated with a thinner (175 mm) layer of hygroscopic insulation. Their mould growth indicator values varied from 2 to 3 at the end of a period of six months. This reflects the increased mould growth risk, although it still remains below the critical level in the elements adjacent to the external surface.

The structure with the Intello moisture barrier ranked between the vapour-tight and X5 air barrier structures. The OSB air barrier caused a slightly higher mould growth in the Intello case, with the 'very sensitive' material.

The hygroscopic structure with plasterboard and material *prone* to mould growth reached a maximum of approx. 2.5 during a six-year simulation period. This level still has to be accepted in external elements and does not reflect such a mould growth risk which could affect the indoor air. Nonetheless, this case reflects increased sensitivity to mould growth compared to the situation where a thicker porous wood fibre board was used as an air barrier.

Summertime condensation has not occurred in the tested cases in the Finnish climate conditions, although the impact of rain and insolation has been configured so as to enhance this phenomenon. The humidity levels of hygroscopic structures open to diffusion in both directions are much more balanced in different exposure situations than in the case of non-hygroscopic and vapour-tight structures. This reduces the occurrence of abrupt peak humidity levels and possible condensation in a more demanding exposure to moisture, for example in warmer climate conditions.

4.7 Roof structures

4.7.1 Test cases

In this survey, structures compliant with Fig. 13 and Fig. 14 were analysed. In the course of the research, specific estimations of wind-protective, thermal insulation, as well as air/vapour barrier materials were used. In all cases the vapour resistance of the inner lining coat was S_d = 0.02m which corresponds very well to highly permeable clay paint. The low inner surface moisture resistance increases the analytical accuracy in the Finnish climate. Table 6 indicates roof structure case studies.

Table 6. Roof structure case studies.

Code	Wind barrier board	Thermal insulation	Vapour/ air barrier	Inside 48 mm space	Other
		YP1 structures:			
X5	24 mm hk	450 mm cellulose fibre	X5	air gap	
X5n	24 mm hk	300 mm cellulose fibre	X5	air gap	
X5e0	24 mm hk	450 mm cellulose fibre	X5	air gap	Emission factor = 0
Ref,hs	24 mm hk	450 mm mineral wool	HS	air gap	
		YP2 structures:			
X5C	24 mm hk	450 mm cellulose fibre	X5	air gap	25 mm plank layer below the metal sheet roof
X5-2	24 mm hk	550 mm cellulose fibre	X5	air gap	Horizontal structure
X5-22	No wind barrier	550 mm cellulose fibre	X5	air gap	Horizontal structure
Ref,hs-22	No wind barrier	550 mm cellulose fibre	HS	air gap	Horizontal structure

The estimated ventilation factor of the 25 mm air gap between the metal sheet roof and membrane amounted to 40 1/h. In the case of slanted roof insulation, the 100 mm ventilation gap between the insulation and the membrane the estimated ventilation factor amounted to 20 1/h (Fig. 13). The air gap of the horizontal roof (Fig. 14) was set to 150 mm in the c~~l~~alculation, and the ventilation factor amounted to 30 1/h. The set ventilation coefficients are realistic, though quite high. Air flow velocity, e.g. in the 15 m long and 25 mm thick air gap below the membrane, amounted to approx. 0.17 m/s. The purpose of estimating sufficiently high ventilation was to ensure that the assessment of functionality depends solely on the thermal insulation structure and, on the other hand, that the structure cooled with counter-radiation is penetrated with a certain moderate amount of outdoor moisture.

The roof was estimated as a glossy metal sheet roof with an insolation absorption rate of 0.20 and a long-wave thermal radiation emission factor of 0.90. The roof is subject to insolation and wintertime counter-radiation. The thermal resistance of snow cover, or other similar layers was not taken into account. Due to estimations, the cooling caused by sky counter-radiation occurs in all seasons; however, the heating impact of insolation is low.

The spaced planking of the metal sheet roof was not modelled, and the top roof layer was reflected as a sole metal sheet layer. In this case, the cooling of the metal sheet surface corresponded with the worst situation, as no heat conductivity resistance or thermal mass of the planking was considered.

In YP1 a structure slanting gently to 14 degrees was estimated, directed southwards. YP2, as an exception to the picture, a horizontal roof was used, which increased slightly the impact of wintertime counter-radiation compared to YP1.

The calculation period is 3-5 years depending on the case.

4.7.2 Results

<u>Slanted roof structures</u>

B~~The b~~oth sides of the wind barrier were ~~the~~ critical parts of the structures. With regard to these places, the mould indicators were calculated by means of simulated temperature and humidity values, either for *very sensitive* or *sensitive* mould susceptibility categories~~y~~. The *very sensitive* category corresponds ~~with~~ to a non-treated pine wood surface, while *sensitive,* in general with construction products ~~with~~ having a wooden surface. Fig. 21 represents YP1 mould indicators of upper surfaces of diagonal insulation structures and Fig. 22 of the wind barrier inner lower surface.

The structures above the air barrier may be prone to mould growth, if they include materials that are *very sensitive.* There ~~has been~~ was no difference in mould growth depending on the thickness of the thermal insulation year, as long as X5 was used as the air barrier. The maximum level of the mould indicator during a four-year simulation period was approx. 3.5 and the yearly trend was rising. With a vapour barrier and mineral wool in the structure, the mould growth speed was slower;~~,~~ however, in the fifth year the maximum also exceeded ~~also~~ level 3 in this structure.

In the case where the sky counter-radiation was excluded, in other words the metal sheet roof ~~cannot~~ could not be cooled down below the outdoor air temperature (X5e0), there was no mould growth risk in the upper layer of the wind barrier, even in the case of the very sensitive material. Also, in the case where there was a 25 mm plank layer (X5C), it was sufficient to prevent ~~from~~ the excessive cooling and growth of moisture levels. In this case, the mould growth indicator also remained ~~on~~ at a safe level, below 1. On this basis, the

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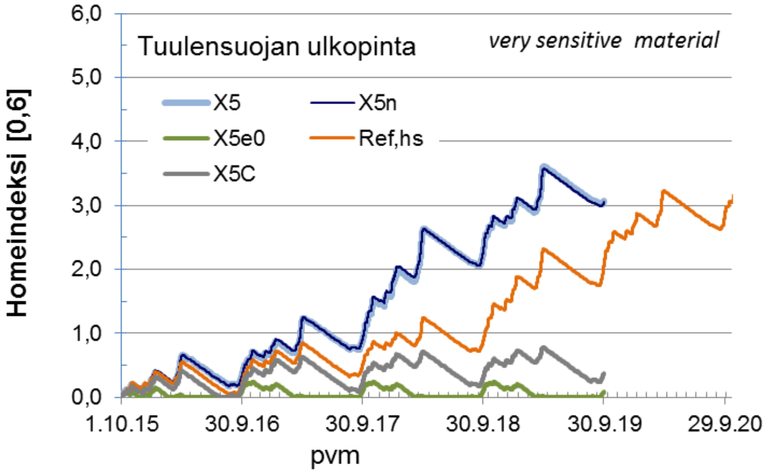
problems associated with the mould vegetation in the roofs were explained with the cooling of upper wind barrier structures caused by the sky counter-radiation.

When the upper layers of the wind barrier were made of materials included in the *sensitive* class, there was no mould growth risk in the structures.



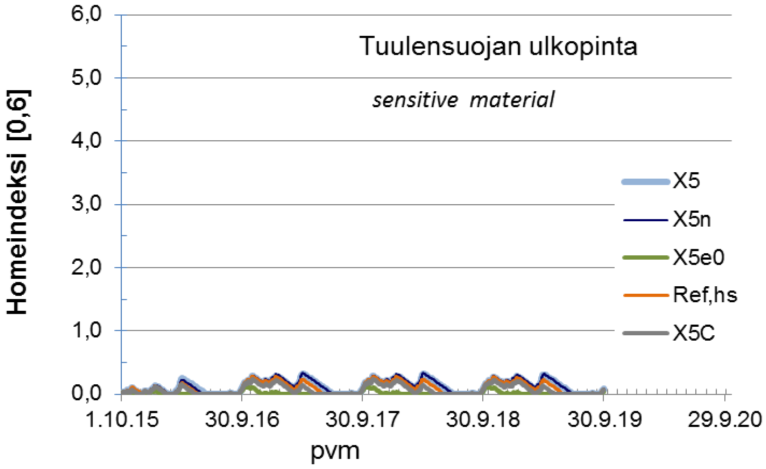


Fig. 21. Calculated mould indicator of the YP1 roof structure outer surface wind barrier in various structure cases. -The material category is very sensitive above and sensitive below.

On the basis of the results, the lower layers of *very sensitive* materials, e.g. layers below the wind barrier, retain their humidity-related functionality even in connection with ‘very sensitive’ materials, e.g. pine wood surface (Fig. 22).

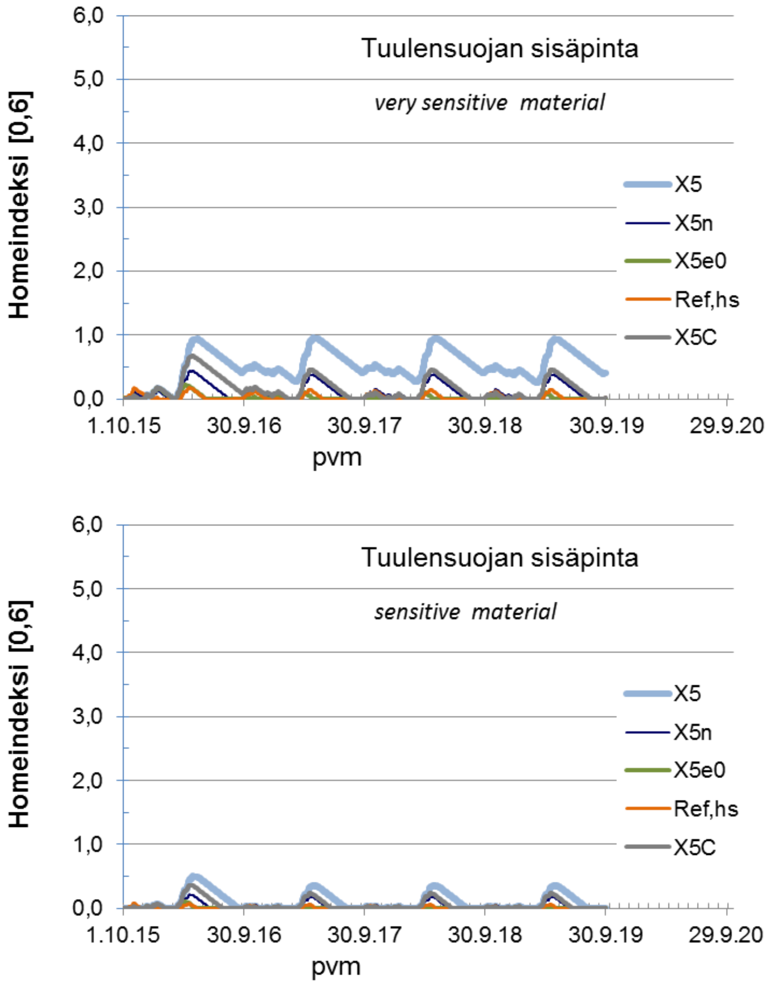


Fig. 22. Calculated mould indicator of the YP1 roof structure wind barrier inner surface in various structure cases.~~-~~ The material category is very sensitive above and sensitive below.

Horizontal insulation structures

Fig. 23 represents the mould growth indicators of horizontal roof insulation in the ventilation gap and on the outer surface of the wind barrier, as well as on the outer surface of Fig. 24 insulation against the wind barrier or ventilation gap.

The thermal insulation layer was thicker in roof YP2 than in YP1 and additionally the horizontal assembly increased the cooling effect of counter-radiation which was visible in the slightly higher calculatory mould indicator values. In the case of the *very sensitive* material category in a structure consisting of an X5 air barrier and 550mm cellulose fibre insulation, the maximum level of the mould indicator of the upper surface of the wind barrier during four years was 4.3. Without the wind barrier in the structure the mould growth indicator kept growing and ~~it~~ reached 5 in the ventilation gap. This value was reached both in the vapour-tight structure insulated with mineral wool, as well as in the structure with X5 air barrier and cellulose fibre insulation.

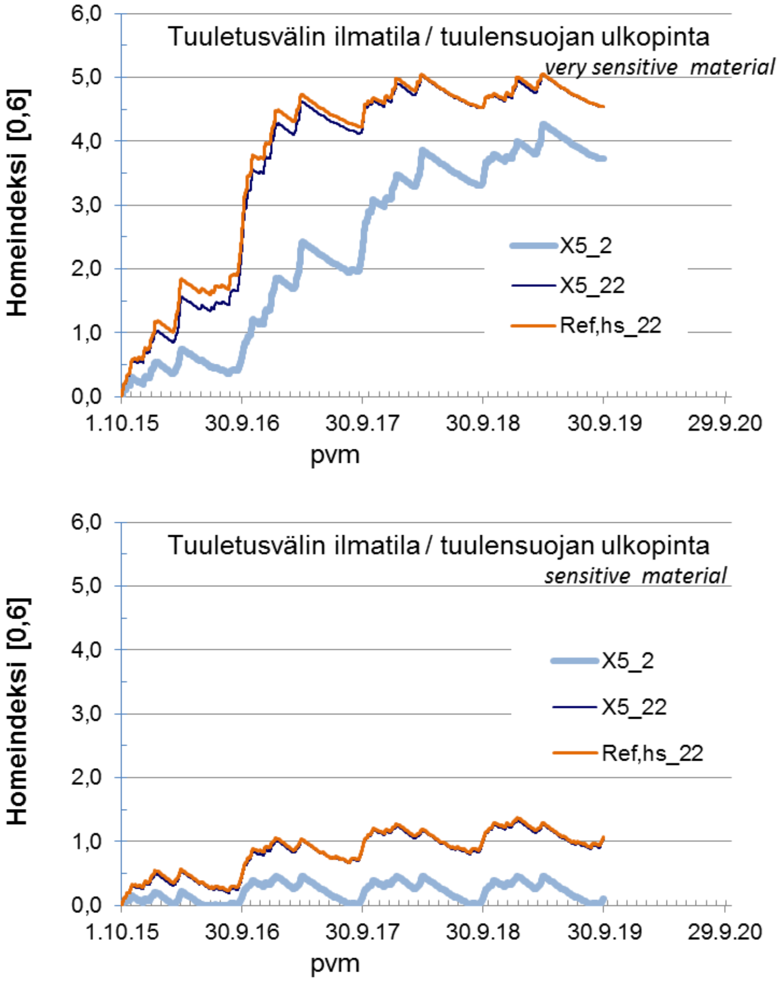


Fig. 23. Calculated mould indicator of the YP2 (horizontal) roof structure ventilation gap/wind barrier outer surface in various structure cases.~~-~~ The material category is very sensitive above and sensitive below.

The result was, to a certain degree, identical ~~with~~ to the mould indicator of the upper surface of the insulation layer, when there was no wind barrier in the structure. Both in the case of hygroscopic and non-hygroscopic structures, a clear calculatory mould growth risk has occurred (Fig. 24).

In a wind-protected case, the interface between the thermal insulation and wind barrier remained ~~near~~ close to 1 in the case of *very sensitive* material and ~~it~~ fluctuated on both its ~~both~~ sides (Fig. 24). During a four-year period, the mould growth indicator of the outer layer fluctuating around 1 did not indicate any risk in terms of structure reliability.

In the case of roof structure YP1, the *sensitive* material category was safe to be used in layers below and above the wind barrier;~~,~~ however, the use of *very sensitive* materials involved a severe risk in the ventilation gap materials and the upper surface of the adjacent insulation or wind barrier.

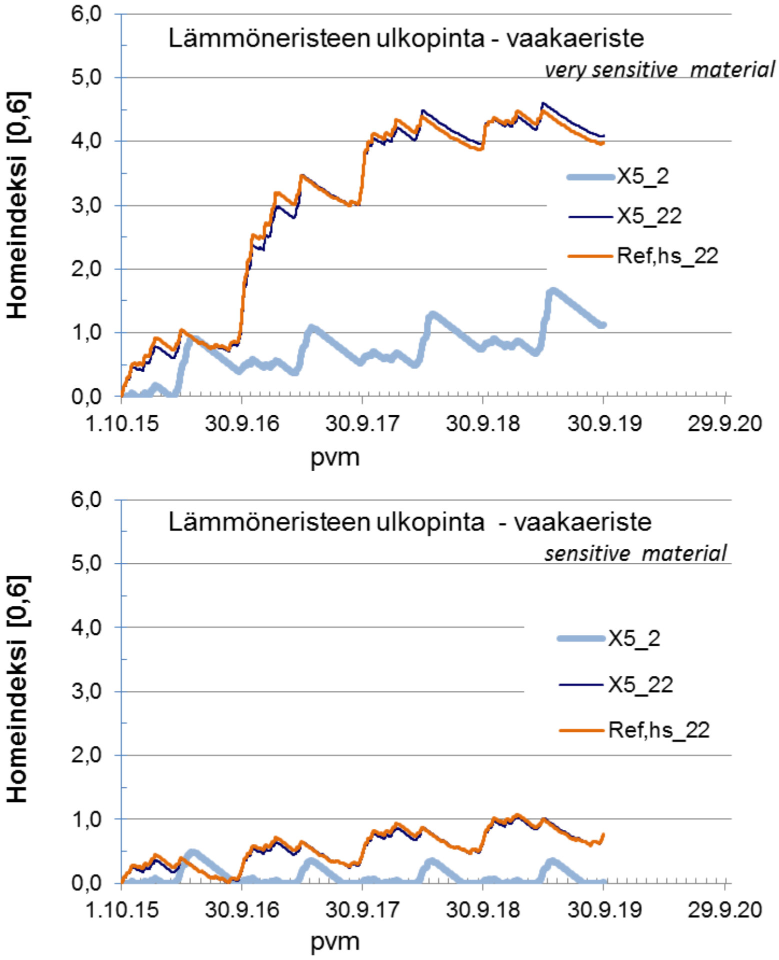


Fig. 24. Calculated mould indicator of the YP2 insulation outer surface wind barrier (horizontal insulation layer) in various structure cases. The material category is 'very sensitive' above and 'sensitive' below.

There was no difference in mould growth risk between the hygroscopic and non-hygroscopic structures, in terms of the ventilation gap. The impact of indoor humidity exposure was therefore irrelevant with regard to the functionality of the ventilation gap in the studied structures.

A tight seaming of the structure below the metal sheet layer, e.g. with planks or another corresponding material, helps avoid excessive cooling of roof structures and the increase of the humidity level, which otherwise may increase the mould growth risk. This solution brings an additional thermal insulation layer into this part of the structure and may work as a hygroscopic and thermal mass, balancing the changes of temperature and humidity. Another method to avoid mould growth risk, is the use of materials with sufficiently efficient fungicides.

4.7.3 Case - Additional insulation of horizontal roof structures

The objective was to clarify the humidity-related functionality of a horizontal roof structure with extra in-blown cellulose fibre insulation. The roof structure was estimated to be directed northwards and inclined to 20 degrees. In the original structure there was 250 mm of mineral wool and a vapour barrier (ren0). 200 mm of cellulose fibre insulation was installed on top thereof as an additional blown-in insulation layer (ren1). As a general estimation, as in the other simulations, the structure was free of air leakages and the air/vapour barrier worked as planned. It is not desired nor possible to simulate the possible errors in structural details. The obtained results of the calculatory mould growth indicator of the ventilation gap and upper surface of the thermal insulation layer are Fig. 25 and Fig. 26.

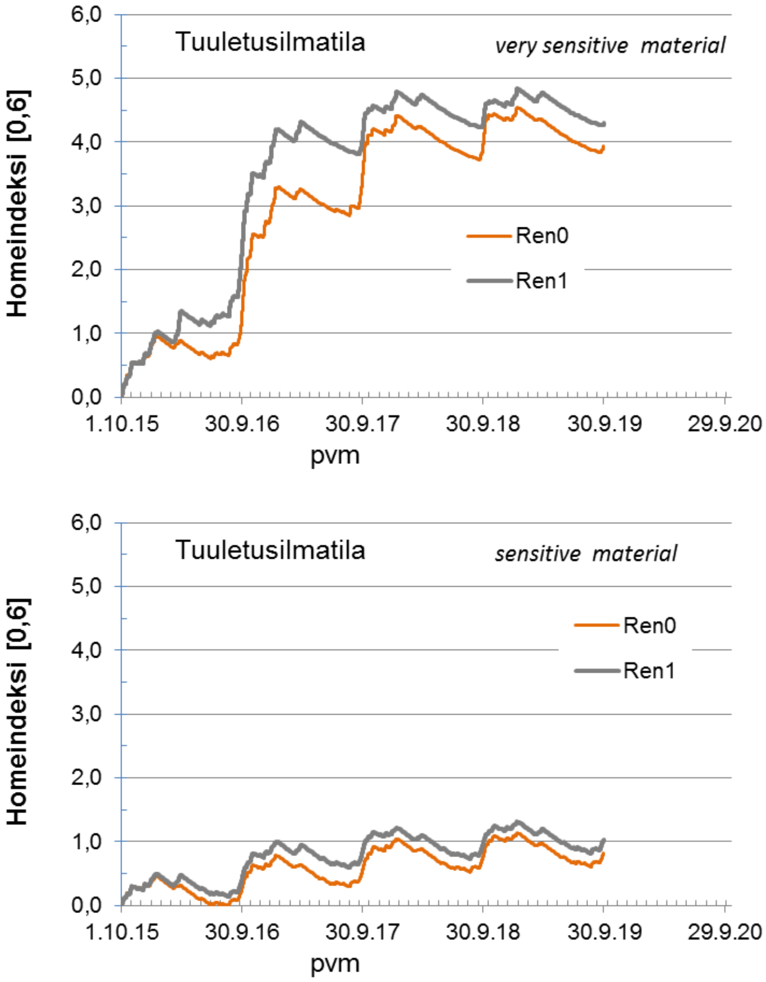


Fig. 25. Calculatory mould growth indicator of the original and insulated ventilation gap in a roof structure. The material category is very sensitive above and sensitive below.

The improvement of the thermal insulation level has affected the functionality of the structure only marginally. Even the heat losses in the original roof structure with a 250 mm mineral wool layer were not sufficient to keep the temperature of the ventilation gap on a sufficiently high level, so that the cooling caused by counter-radiation would not cause an increased mould growth risk in the ventilation gap in the case of *very sensitive* materials. The mould growth risk detected in the calculations was not caused by the thick insulation, but by other functional factors of the structure. The functionality of *sensitive* materials is also secure in the currently studied cases.

Also here, the biggest risk involved the cooling down of the metal sheet surface and the related temperature levels and local humidity values. In terms of functioning, the upper surface of the insulation and especially the ventilation gap were the critical areas.

No moisture accumulation or high humidity levels were recorded on the interface of the cellulose fibre or mineral wool insulation. After a short drying phase of initial moisture, the relative humidity of the interface was approx. 70% RH at the maximum, so it was not risky from the perspective of functionality.

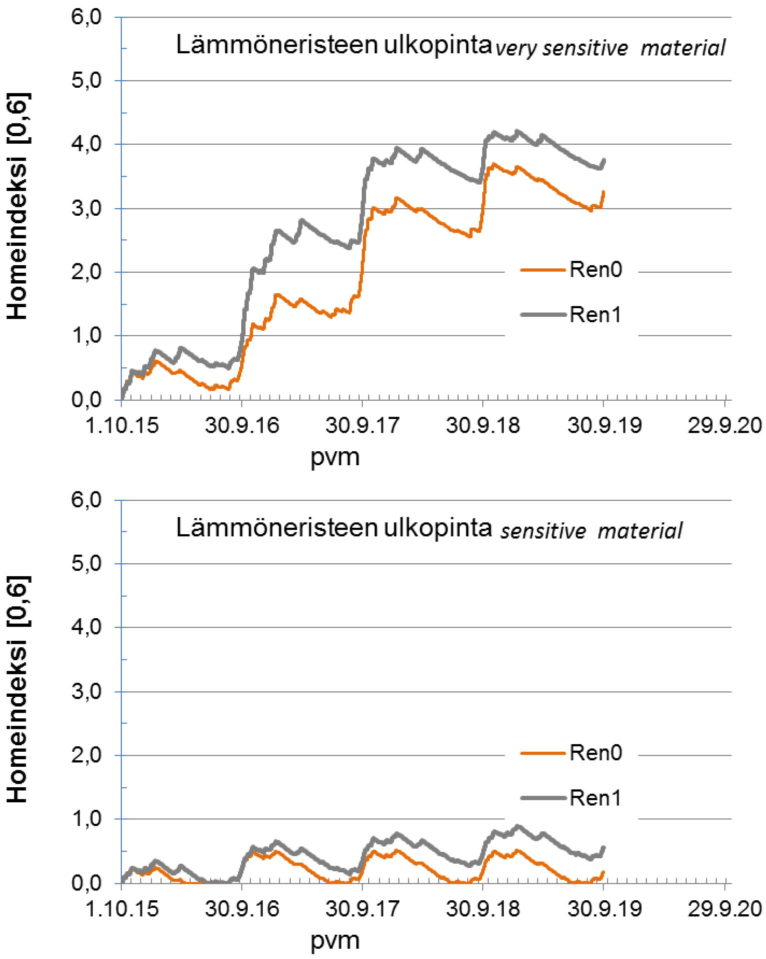


Fig. 26. Calculatory mould growth indicator of the upper surface of the insulation layer in the original and insulated roof structure. The material category is very sensitive above and sensitive below.

4.7.4 Summary of humidity-related functionality of roof structures

In the analysed cases, metal sheets were used as the top roof layer. Radiation properties set for metal sheets, as well as the thermal and hygroscopic mass of the battens and other bearing elements missing from the one-dimensional analysis, led to increased sub-cooling due to the counter-radiation of the sky. The ventilation of the structures was set to moderately high, so that outdoor moisture would penetrate into the structure, in order to maintain the high humidity level in the under-cooled elements. The analysis results provide a reliable and conservative image of the structure functionality. The primary goal of the analysis was to compare the humidity-related functional security of hygroscopic and non-hygroscopic structures in light roof structures.

In terms of the humidity-related functionality of the tested roofs, the critical areas were the ventilation gap and bordering layers.

The impact of the hygroscopic insulation structure (type of thermal insulation and particularly the vapour permeability properties of the air barrier) according to the calculations were visible only in the conditions of the outer surface of the wind barrier. In the lower layer of the wind barrier, there was no difference on the upper surface or ventilation gap in the scenario without the wind barrier. The difference in the conditions of the upper surface of the wind barrier was visible in the quicker growth of mould in the hygroscopic structure. In both structural cases *very sensitive* material has caused mould growth in critical conditions. Also in this case, the difference between the hygroscopic and non-hygroscopic structure function was marginal: In both cases the mould growth risk was obvious with the estimations made, and the only difference was in growth speed. Apart from the vapour permeability of the air barrier, this discrepancy was also caused by the higher initial humidity of the hygroscopic insulation material (initial balancing humidity 80% RH).

In wind-protected structures the bottom layers of the wind barrier were also secure in the case of *very sensitive* materials.

In other structural elements and *sensitive* materials, the differences between the hygroscopic and non-hygroscopic structures were marginal. Cellulose fibre insulations or the vapour permeability of the air barrier did not intensify mould growth in practical aspects. For example, the conditions of the ventilation gap or outer surface of horizontal insulation without a wind barrier generated approximately similar calculatory mould growth indicator values.

The most important factors for the humidity-related functionality of the analysed structures were the cooling of the ventilation gap caused by counter-radiation, as well as outdoor moisture brought in by ventilation. The metal sheet roof cools down due to the counter-radiation of the sky, which causes the cooling of the ventilation gaps and its structures, as well as increasing their relative humidity level. If the undercooling were to be prevented by insulating the metal sheet roof, the conditions in ventilation gaps could be regarded as corresponding with the outdoor conditions, whereas the ventilation would not cause more problems than in the wall structures.

The susceptibility to mould bears a great influence on the occurrence of mould vegetation. In difficult structural cases the material must be selected in order to tolerate the conditions.

Cellulose fibre insulations may be used on top of mineral wool insulation as extra insulation without any problems. No accumulation of moisture or increased humidity levels were recorded on the border between cellulose fibre insulation and the original mineral wool layer. While performing insulation retrofitting, the general requirements of structural functionality must be observed: Ensuring sufficient ventilation, sufficient air/vapour tightness of the old structure, functionality of the roof and membrane, etc.

When the original insulation layer was increased from 250 mineral wool with 200 mm of cellulose fibre insulation, the mould indicator of the insulation outer surface reached a calculatory value of 3.6 in the original structure, whereas in the retrofit case it was 4.1. In this case, the material was assumed to be *very sensitive* in terms of susceptibility to mould growth. The difference was caused by higher heat loss into the ventilation gap of the roof structure. Even the relatively high heat loss in the original structures have not been sufficient to keep the structure mould-secure, as there were other functional problems with the structure. In this calculation scenario, the issue was the intensive cooling down of the light structure caused by the counter-radiation of the sky.

5. Interaction between the structure and indoor air

In this section of the project, the humidity interaction between the indoor air and the structure was examined with regard to the relative humidity of indoor air and heat loss via the walls. The survey was performed on a selected exemplary structure. The analysis was simplified by setting a step change value of the indoor air relative humidity at the beginning of the survey, when the structure humidity was balanced at least in the elements adjacent to the inner surface on a level corresponding with the initial status of the step change. The fluctuation of indoor humidity is visible as moisture flow between the structure and indoor air. The volume of moisture flow was correlated with the change of indoor humidity.

The vapour liquefied in the structure warms up the structure surface and the evaporating vapour cools it down. When the inner surface of the structure is used as a balance border of conduction heat losses, the surface humidity change can be traced down in the heat flow through the surface. In the case of condensation, heat losses are reduced and in the case of evaporation they grow, compared to the situation where there is no moisture flow between the structure and indoor air.

Wall structure US1 was selected for analytical purposes (Fig. 12 and Fig. 27). A small vapour resistance was simulated on its surface, corresponding with minimum coating, that is Sd = 0.02 m, so that the structure would reflect the maximum realistic usage potential of the moisture capacity.

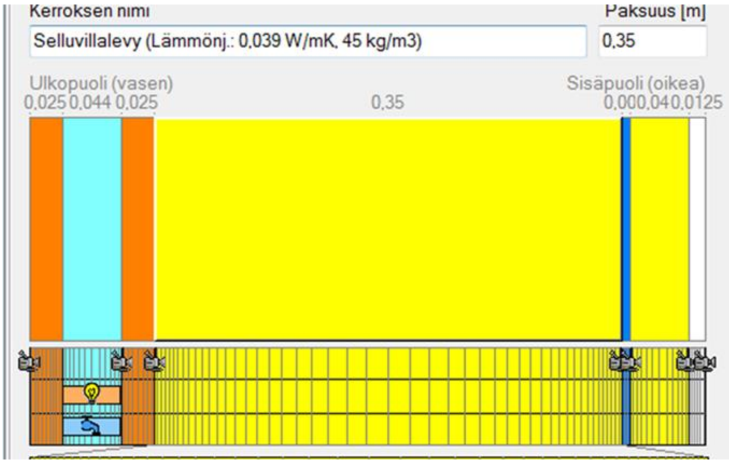


Fig. 27. Cross-section of the test structure in WUFI.

5.1 Step change of indoor air humidity 30 % RH – 60 % RH

In this case, the initial humidity of thermal insulation layers and the initial humidity of the interior panel almost corresponded to a dry condition, 30% RH, while the outer layers remained in a balanced condition of 80% RH corresponding to initial humidity. In the beginning of the analysis the indoor air humidity grew to 60% RH and remained stable for the entire test period. Indoor temperature was stable (+20 ^{o}C) during the entire test period and the outdoor air conditions were compliant with weather data for Vantaa, Finland. The calculation began on 1st October. The analysis was carried out over a 10 day period.

The situation reflects a simplified impact of the rapidly changing indoor air exposure to moisture on the humidity values, as well as the temperature of the inner surface and heat loss via the structure. The described situation does not reflect the real conditions with regard to rapid fluctuation and its duration. The applied relative humidity values correspond with the levels that are practically possible. The fluctuating situation also allows us to obtain a view of the structure's functionality during cycles exceeding 24 hours.

The test structure was US1 (Fig. 12). The specific cases are presented in Table 7. On the basis of the studied cases the impact of thermal insulation, air/vapour barrier and internal coating on moisture flows and heat losses via the structure. As a reference case, mineral wool insulation (20 kg/m^3) in internal and external insulation chambers (ref,hs) was used. In other cases, the 350 mm insulation chamber was filled with cellulose fibre insulation (40 kg/m^3). The impact of density of cellulose fibre was reflected by using artificial densities 70 kg/m^3 and 120 kg/m^3 of the inner 48 mm thermal insulation layer, the moisture capacities of which were estimated as directly proportionate to density.

The inner panel (13 mm plasterboard) was coated with the least vapour-resistant clay paint, Sd = 0.02 m. The second reference case was a structure with cellulose fibre insulation, X5 air barrier, and an almost vapour-tight inner surface, Sd = 0.02 m (ES100).

Table 7. The analysed wall structure cases with the step change of indoor air relative humidity.

Code	Thermal insulation	Vapour/ air barrier	Thermal insulation, inside 48 space	Inner surface moisture transfer resistance S_d (m)
E40	350 mm cellulose fibre	X5	cellulose fibre 40 kg/m^3	0.02
E70	350 mm cellulose fibre	X5	cellulose fibre 70 kg/m^3	0.02
E120	350 mm cellulose fibre	X5	cellulose fibre 120 kg/m^3	0.02
Ref,hs	350 mm mw	HS	mineral wool 20 kg/m^3	0.02
ES100	350 mm cellulose fibre	X5	cellulose fibre 40 kg/m^3	100

In the case of the growth of indoor air humidity, moisture started to move as vapour diffusion into the structure, the balance humidity of which corresponds with the original lower relative humidity. Fig. 28 represents the moisture flow densities from indoor air into the structure after the change of situation, while Fig. 29 reflects the total amount of moisture penetrating into the structure per surface unit. Step change in indoor air causes a strong peak in moisture transfer immediately in case of change. Moisture flow decreases from now on and its fluctuation depends on the moisture capacity of the structure and the vapour permeability of the internal layers.

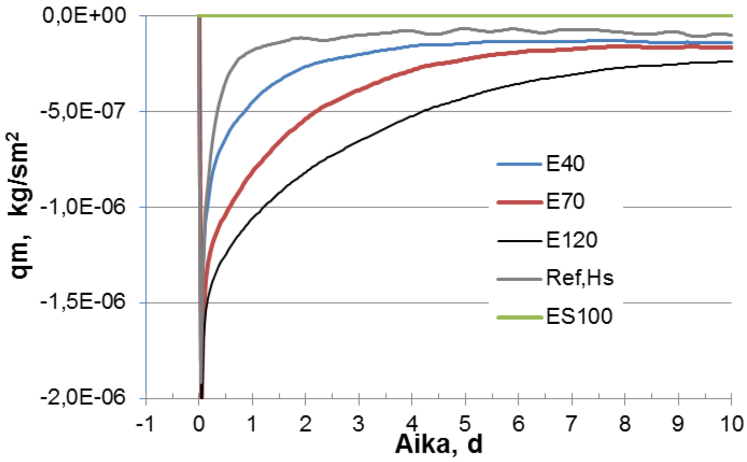


Fig. 28. Density of moisture flow between the structure and indoor air after the step change (t = 0). Negative value reflects the moisture flow in the structure. Aika=time.

In the case of a structure which is vapour-tight from inside, there is no moisture passing inside the structure. In the Ref,hs case the moisture flow is directed slightly inside the mineral wool cavity behind the plasterboard and vapour barrier. The higher the density of cellulose fiber insulation in the internal cavity, the longer the duration of moisture ingression into the structure. This corresponds with the assumptions, as the properties of the structure's inner layers are of the greatest importance on the moisture interaction with indoor air. The impact of thermal insulation begins to be visible within 1-2 hours from the beginning of change; first of all, moisture penetrates into the plasterboard and balances its humidity.

The biggest differences are visible during a few days from the beginning of the change, when the humidity of hygroscopic structures has reached a somewhat stable level and the humidity fluctuation is still visible in the structures with the highest capacity.

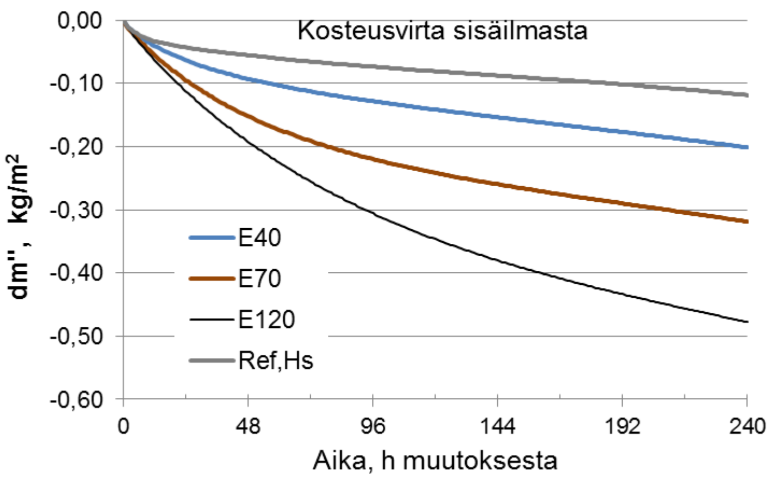


Fig. 29. Amount of moisture that has penetrated from indoor air into the structure since the beginning of step change.

Fig. 30 visualises the change of humidity on the different sides of the inner thermal insulation cavity in the reference case (ref,hs), as well as in the basic case of a structure insulated with cellulose fibre (E40). In the case of the smallest moisture capacity, the humidity level balanced itself rapidly near to the final situation. Fluctuation is caused by temperature change which is visible in the structure temperatures and consequently in balance humidity values.

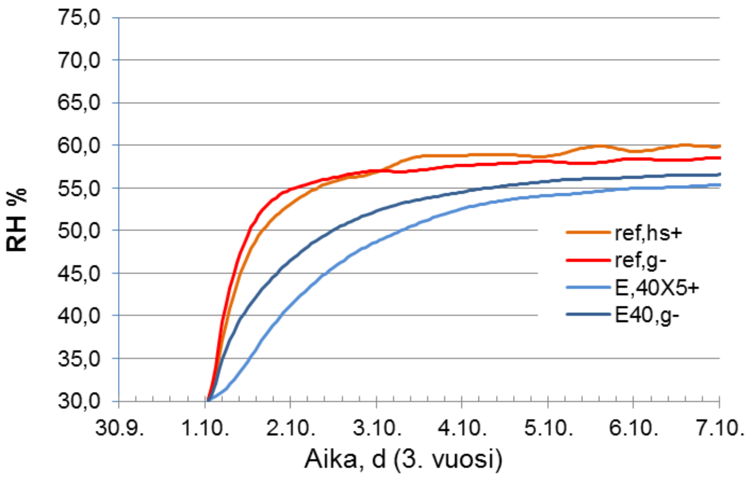


Fig. 30. The change of relative humidity behind the interior panelling (g-) and on the air barrier surface (X5+ and hs+) in two different structure cases: hygroscopically open cellulose fibre insulation structure (E40) and vapour-tight mineral wool insulated structure (ref,hs). Time, 3rd year.

When moisture moves by means of diffusion from indoor air inside the wall and is liquefied therein, the structure's surface layer is warmed up. The conduction heat loss via the structure inner surface reflects its functionality in terms of heat. When the structure is warmed up due to heating, its heat loss decreases. Fig. 31 reflects the calculated heat current densities [W/m^2] via the inner surface balance border and Fig. 32 conduction heat loss during a 10 day test period [kWh/m^2].

When a significant amount of moisture has passed into the structure from indoor air, the condensation of moisture causes the conversion of heat loss into heat flow from the structure into indoor air. The heat flow inside continues until the heat current brought in by the condensing moisture is smaller than the conduction heat loss of the structure.

In the case of a structure that is vapour-tight from inside, the impact of moisture on heat loss was irrelevant. In the case of a vapour-tight ref,hs structure the heat current density changed to negative (heat loss) approx. 24 hours since the change and in the basic cellulose fibre insulation case - after approx. 48 hours. The heat current direction of the densest cellulose fibre insulation (case E120) from the structure to indoor air lasted for approx. 6.5 days.

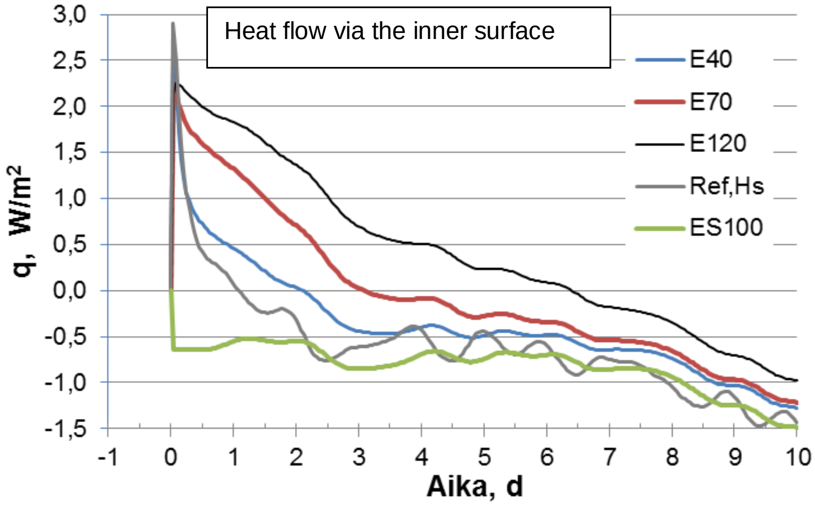


Fig. 31. Conduction heat current via the inner surface.

The conduction heat loss of the 10-day test period (Fig. 32) in case of a structure isolated against indoor moisture amounted to approx. -0.18 kWh/m^2, in the Ref,hs case approx. -0.16 kWh/m^2, while in the basic case of cellulose fibre insulation E40 approx. -0.11 kWh/m^2 and with the highest capacity E120 a heat amount of +0.05 kWh/m^2 penetrated into the indoor air.

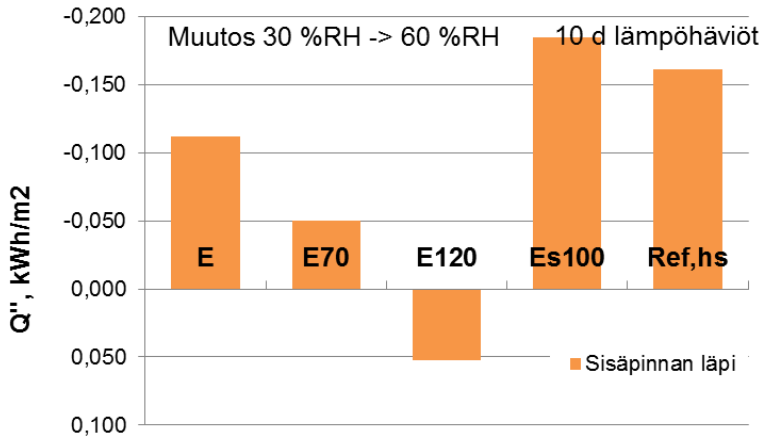


Fig. 32. Conduction heat loss via the structure (inner surface) after a step change of indoor air humidity (30 % RH -> 60 % RH) during a 10-day test period.

The change of conduction heat loss was caused by the condensation of vapour in the structure. Fig. 33 represents the heat current calculated on the basis of the moisture current and Fig. 34 specifies the conduction, latent and total heat amounts in the test period. Although the conduction heat loss has decreased greatly, the total heat balance of the ambient air has been similar in the different cases. This means that the additional indoor air moisture loads are used in order to reduce heat loss in the case of changing indoor air properties. The reusable heat energy is obtained from excessive moisture and its balancing under the moisture exposure may additionally improve indoor air conditions.

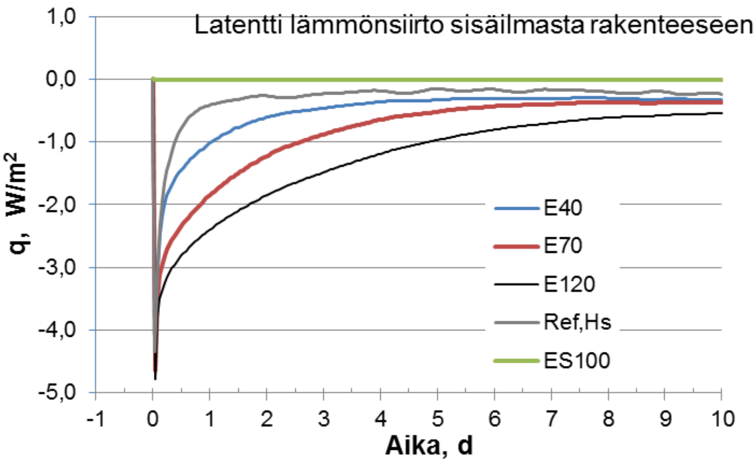


Fig. 33. Latent heat transfer from indoor air into the structure.

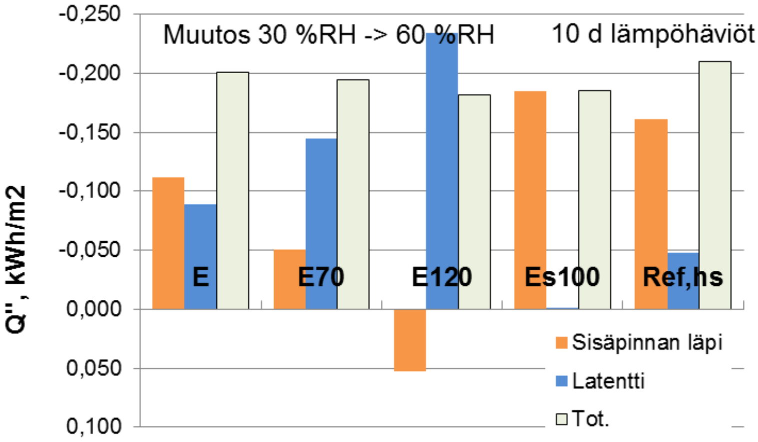


Fig. 34. Heat loss via the structure after a step change of indoor air humidity (30 % RH -> 60 % RH). Conduction heat loss through the wall structure, latent heat transfer caused by the change of form of moisture moving from indoor air into the structure, and their sum in different test structures.

The usability of this phenomenon depends on the amount or frequency of the available excessive moisture, as well as on the humidity level on which the structure has stabilised itself before such an exposure. In addition, the moisture bound into the structure at least partially tries to escape back into the indoor air. This again balances the interior humidity, so that the conditions are more balanced and probably more pleasant, than in a non-hygroscopic environment. At the same time, the moisture passing from the structure into the interior, binds heat while evaporating from the materials into the air. This phenomenon increases the conduction heat loss of the structure, as presented in the next step change analysis, where the change of indoor air conditions takes place towards the drier area.

5.2 Step change of indoor air humidity 60 % RH – 30 % RH

In this case, the initial humidity of thermal insulation layers and the initial humidity of the interior panel was on its entire surface 60% RH, while in the beginning the relative humidity of indoor air changes to 30% RH. The test environment corresponds, in other respects, to the previous step change, where the change direction was different.

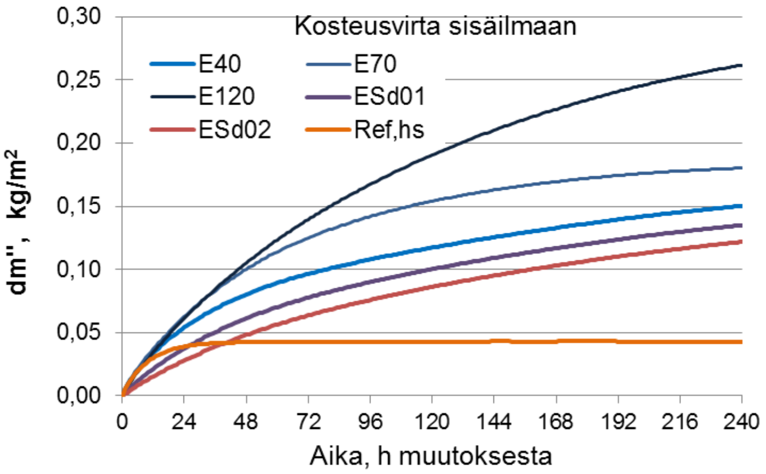
In addition to the cases covered with the previous step change analysis, the impact of interior surface vapour resistance on the moisture flow between the structure and indoor air was examined thoroughly. Additional tests are described here Table 8.

Table 8. The additional cases of wall structure analysis with the step change of indoor air relative humidity. In the case of Ec there was no heat caused by change of form accounted for in the numerical result.

Code	Thermal insulation	Vapour/ air barrier	Thermal insulation, inside 48 space	Inner surface moisture transfer resistance S_d (m)
ESd01	350 mm cellulose fibre	X5	cellulose fibre 40 kg/m^3	0.10
ESd02	350 mm cellulose fibre	X5	cellulose fibre 40 kg/m^3	0.20
Ec	350 mm cellulose fibre	X5	cellulose fibre 40 kg/m^3	0.02

Fig. 35 reflects the total amount of moisture flow accumulated in the indoor air from the structure in different test structures during a 10-day test period and its first 24 hours. Along with the growth of the vapour resistance of the interior panelling, its impact is noticeable particularly at the first stage of moisture transfer. In the case of a surface resistance of S_d = 0.1 m the amount of moisture exceeded the amount of moisture escaping from a reference structure (Ref,hs) in approx. 28 hours from the beginning of the change and in case S_d = 0.2 m the respective time was ca. 40 hours.

The significance of vapour resistance is critical in terms of taking advantage of moisture capacity. The goal is the smallest resistance possible, so that the capacity may be used efficiently. In the case of growing resistance, the moisture flow decreases and is distributed over a longer time.



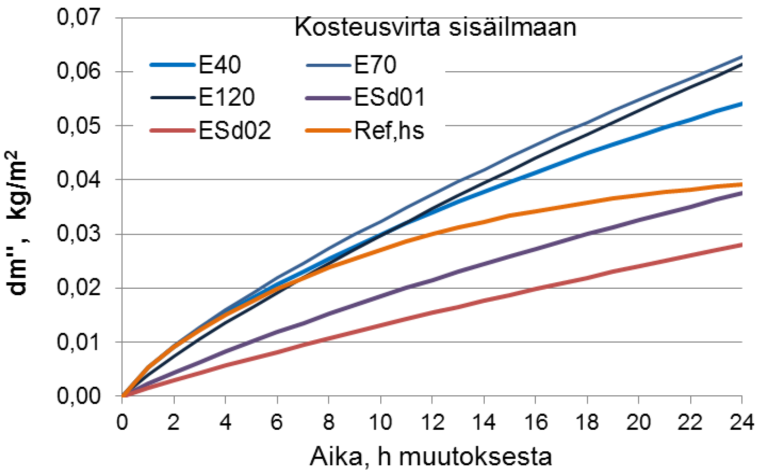


Fig. 35. Vapour current densities from the structures to indoor air in different cases are after a step change of indoor air humidity (60 % RH -> 30 % RH). Above is presented the entire 10-day period and below the first 24-hour period since the change.

Fig. 36 reflects conduction heat loss during the 10-day test period through the structure's inner surface. In the diagram, the additional impact of latent heat transfer on heat loss via conduction. Conduction heat loss via the inner surface grows proportionately to the vapour movement from the structure to indoor air. During a 10-day period, the impact of the surface vapour transfer coefficient has become balanced compared to the differences between the various cases in terms of initial moisture transfer.

Analogically, the latent heat transfer increases indoor air enthalpy with regard to the latent heat of the incoming vapour.

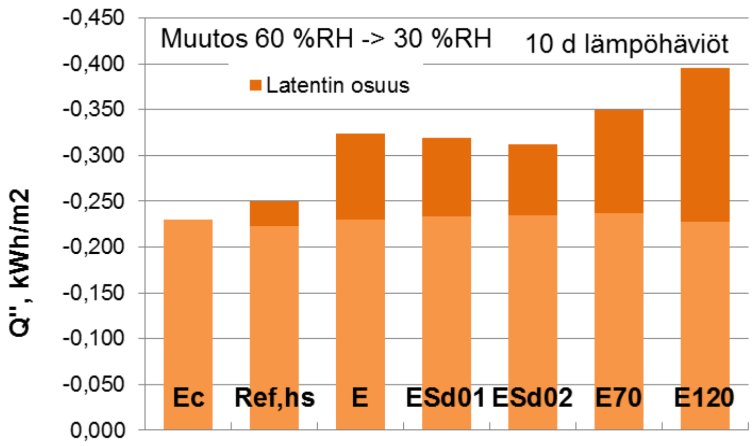


Fig. 36. Conduction heat loss through the inner surface during a 10-day period after a step change of indoor air humidity (60 % RH – 30 % RH). The partial impact of latent heat transfer subdivided from conduction heat loss.

5.2.1 Enhancing moisture interaction with indoor ventilation

The objective of this survey is to clarify how the ventilation flow of indoor air in the internal 48 mm insulation cavity could improve the humidity interaction between indoor air and the structure. For this purpose, two scenarios were analysed. In both cases the room was insulated with a 40 kg/m^3 cellulose fibre insulation layer of 48 mm (Table 9). Here the same step change was examined (60 % RH – 30 % RH) as in the previous section.

Fig. 37 presents the principles of indoor air ventilation. The analysed cases are simplified, e.g. the barrier between thermal insulation and air flow has not been modelled. The objective is to evaluate exclusively the potential of dynamic usage of moisture capacity.

In the second case (Edyn1), the interior panelling surface vapour resistance amounted to Sd = 0.2 m, while the indoor air flow was estimated in a 20 mm air gap at 15 1/h. The cellulose fibre insulation layer on the outer surface of the cavity was 28 mm thick, while the air gap was located between this insulation layer and the plasterboard. The ventilation factor corresponds to approx. 1 cm/s flow speed at 2.5m of wall height, which can easily be obtained in gaps, even with small temperature differences.

In the second case, the surface resistance amounted to Sd = 0.02 m and the indoor air flow ventilated the structure by infiltrating the 48 mm thick insulation layer at a ventilation coefficient of 10 l/h. This corresponds with approx. 7 mm/s flow velocity via the insulation layer.

Table 9. The additional cases of dynamic wall structures ventilated with indoor air with the step change of indoor air relative humidity. In both cases there was 48 mm of 40 kg/m3 dense cellulose fibre insulation on the inner side.

Code	Thermal insulation	Vapour/ air barrier	Indoor air circulation in 48 insulation cavity	Inner surface moisture transfer resistance S_d (m)
Edyn1	350 mm cellulose fibre	X5	20 mm gap, n = 15 1/h	0.20
Edyn2	350 mm cellulose fibre	X5	48 mm insulation cavity, ventilation 10 1/h	0.02

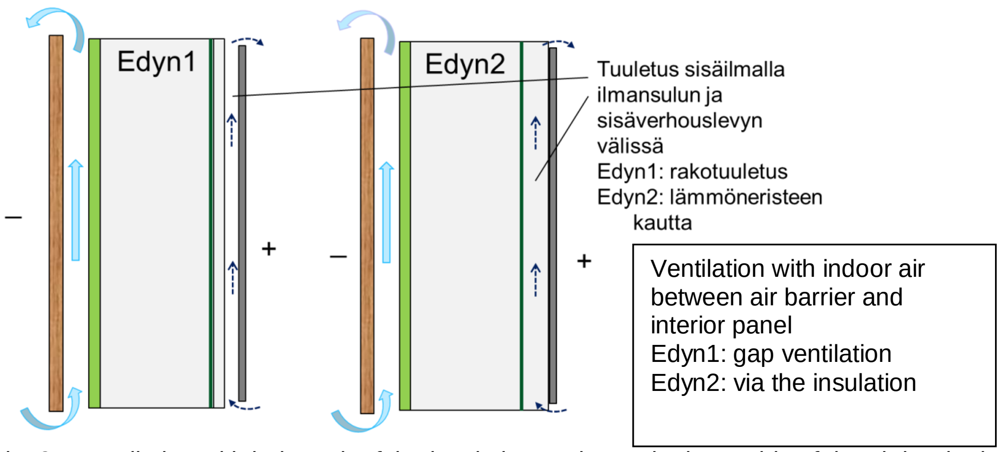


Fig. 37. Ventilation with indoor air of the insulation cavity on the inner side of the air barrier in two test cases.

Fig. 38 lists the results of ventilated structures and the comparable structures. The results indicate a change of the humidity level of the inner insulation layer and plasterboard (moisture transfer to indoor air) during the first 24 hours since the change of conditions. On the basis of the results, it is evident that ventilation with indoor air enhances the exchange of latent moisture with the interior. In the case of a surface resistance of Sd=0.2 m, ventilation improved the moisture transfer to a similar level as with Sd=0.02 m, but without indoor air ventilation. When the ventilation passed through the entire thermal insulation layer (Edyn2) and the surface resistance was S_d = 0.02 m, moisture exchange intensified itself again.

The use of interior ventilation may be a significant factor for the enhancing of humidity interaction between the structure and indoor air. The clarification of its functionality, effect maximisation and the presentation of practical solutions require further research.

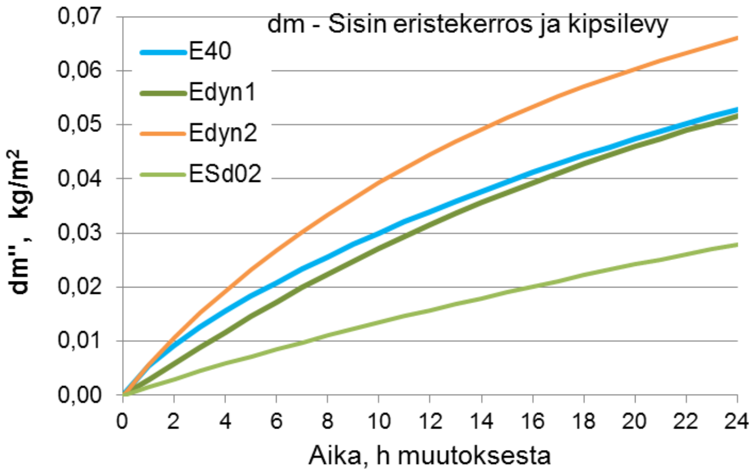


Fig. 38. The change of humidity in the innermost 48 mm insulation layer and interior plasterboard during the first 24 h since the change in two dynamic cases and their comparative cases.

5.2.2 Surface temperature change on the basis of tests

By means of structures and conditions applied in the calculatory analysis, the temperature difference between surface and indoor air obtained in the calculations after step change amounted to 0.3-0.4^{o}C during the condensation of vapour in the structure. Still, Nore /25/, has measured significantly higher temperature differences in laboratory conditions. After the relative humidity grew from ca. 20 % RH to ca. 90 % RH, the moisture absorbed in the wood panel increased the panel surface temperature by the abundant 2.5 ^{o}C (Fig. 39). On the other hand, the measurement time was short, and the peak level was achieved in approx. six minutes from the beginning of the change. The time axis used in the calculation was one hour, so the calculatory analyses should also be done for shorter change periods.

The result shows that the phenomenon is rapid and strong. It allows for the immediate influence upon the indoor air conditions, when the structure's surface temperature increases under growing vapour exposure. Nore presents an idea to save on bathroom heating: While taking a shower, hygroscopic wall surfaces warm up quickly, which is soon sensed in heat comfort. Therefore, the bathroom air temperature could be lower than now. When the wall surface temperature grows during exposure to humidity, the experienced heat comfort of the ambient air remains at a good level. Thanks to this, a possible lower bathroom temperature setting could generate savings on heating. This is one of the subjects that requires further research, also in terms of applications of structures filled with cellulose fibre insulations.

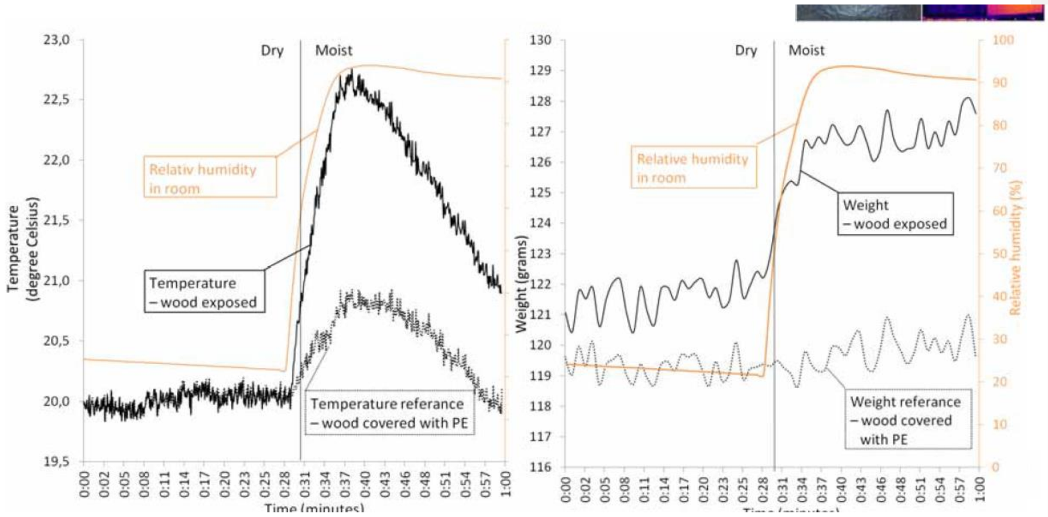


Fig. 39. Empirically defined surface temperature change on the wood panel surface upon a change from 20% RH to 90% RH /25/.

5.3 Summary of the humidity interaction survey

On the basis of the earlier analysis, the transfer of moisture between the structure and indoor air is of great significance for the humidity and comfort of indoor air. In addition, the moisture movements may severely alter the conduction heat loss in the structure during a dynamic situation.

Indoor air impacts are of greater importance in insulated structures, where the partial pressure gradients of temperature and vapour are normally smaller than in less insulated structures. In this case, small changes of humidity or temperature of adjacent layers to the structure of the inner surface may also influence the moisture and heat flow between the structure and indoor air, or even reverse the current direction. Due to the same reason, the hygroscopically active layer of insulated structures may be higher than in the case of those less insulated.

According to the previous research, hygroscopic structures allow us to significantly reduce the fluctuation of indoor air relative humidity caused by exposure: On the basis of calculations and field surveys, the increase of exposure during 24 hours amounted to approx. 15% RH in the case of hygroscopic structures, as in corresponding conditions of non-hygroscopic structures it was 30% RH. Even conditions and the reduction of extremely low and high relative humidity levels improves the heat comfort, living experience and healthiness.

The moisture condened in the structure increases the inner surface temperature and analogically reduces the heat loss passing through the structure. The heat current direction may ~~be~~ even be reserved under the influence of drastic changes of humidity. In this case the structure's surface temperature may exceed the ambient temperature, causing the heat loss currents to be reversed towards indoor air. The impact time of latent heat transfer depends on the force and duration of moisture movement.

After the step change of the relative humidity of indoor air (from 30% RH to 60% RH), the structure with cellulose insulation conducted heat into the indoor air during the test period at the beginning of October for approx. 48 hours since the change of conditions. By increasing the hygroscopic mass in the insulation layer adjacent to indoor air, heat conduction towards indoor air lasted for more than six days. For this purpose, a constant high humidity of indoor air since the change situation and the hygroscopic mass of the structure, is required. The size and length of impact depends also on the outdoor conditions and the structure's U value.

When the structure's humidity moves indoors, the conduction heat loss through the structure grows. As the structure has a roughly stable humidity level during the year, the impact of humidity currents on heat loss during the year is principally low, because the condensing and evaporating moisture flows between the structure and indoor air compensate ~~-~~each other. The usage of moisture loads in the right time for the reduction of heat losses may still - generate significant benefits with regard to the thermal functioning of hygroscopic structures. This requires control of the interoperation of indoor air, ventilation and structures. The more detailed modelling of these processes requires further research in various climates.

Structure ventilation with indoor air may significantly enhance the functioning of dynamic structures and ~~it~~ may become a solution which allows us, at least partially, to eliminate the vapour resistance caused by surface coating and the resulting suppression of dynamic fu~~e~~nctionality. The second method is the use of such paint products which enable the free transfer of vapour through the surface, provided that their washability and appearance meet~~s~~ the relevant criteria.

6. Necessity of further research - project outline

On the basis of this survey, the use of cellulose fibre insulations with ~~the~~ adequate structural solutions may generate noticeable advantages in terms of humidity-related functionality. The existing knowledge and current calculatory research performed for the specific scenarios provide a view of the usage potential. The accurate clarification of functionality of construction applications and dimensioning of the various factors for the ensuring of optimal functioning requires additional numerical analyses and possibly the monitoring of empirical and pilot objects.

On the basis of such surveys, it should be possible to identify the various research forms which would allow for the examination of the specific applications of cellulose fibre insulations in Europe. These are presented below, divided thematically.

1) Interaction between structures and indoor air - Improvement of indoor air comfort

   The existing knowledge can be applied in various climate conditions with the consideration of the typical practice of room temperature control and ventilation. The goal is to indicate the impacts of hygroscopic structure applications on indoor comfort and to develop and present the best solutions for the different conditions.

2) Interaction between the structure and indoor air - structure temperature fluctuation and reduction of heat loss

The vapour transfer between the structures and indoor air, as well as their changes of state may significantly influence the temperature and heat currents in the structure. The use of moisture and heat dynamics at the right time may help to improve thermal comfort and control the heat loss. It is possible to take advantage of this phenomenon in various climate conditions. In addition, the humidity and heat flows occurring in rapidly changing dynamic situations are analysed, together with their possible usage potential.

3) Humidity-related functional safety of structures in different climate conditions

   The various principles and advantages of humidity-related functionality of cellulose fibre insulations in the different climate conditions: Central and South Europe, as well as the specific dynamic indoor air moisture loads.

4) New cellulose fibre insulation products

   Evaluation of the significance of cellulose fibre product properties among others in terms of humidity-related functionality. For example, products of high moisture capacity, their other advantages (acoustics, partition walls, etc.).

5) Empirical comparison of different insulation structures

   Empirical confirmation of functionality of structures insulated with cellulose fibre and their advantages compared to non-hygroscopic products. For example, hot box measurements in controlled conditions corresponding with the real situation. Possible impact of convection on heat loss.

Out of the aforementioned five themes, a project plan will be drafted and developed in order to form a European research project. This project may be carried out in different stages, to be determined in the preparatory period.

Other possible themes, which are not of primary interest in terms of the European applications or the sole position of insulation manufacturer:

- Combining of ventilation and dynamic structure in terms of comfort and energy efficiency
- Roof insulation retrofit - requirements for old structures
- Roof structures - damping of counter-radiation

7. Summary

During this survey, the basics of the humidity-related functionality of structures insulated with cellulose fibre were analysed and the operation of exemplary structures has been modelled with the mould growth evaluation method as the main criterion.

While comparing the operation of hygroscopic cellulose fibre insulations and non-hygroscopic air-filled fibre insulations, there is no difference between them in terms of humidity-related functional safety in the Finnish climate and vapour exposure generated in dry rooms. The main difference in construction applications is the fact that in the case of thermal insulation, the vapour barrier has been frequently substituted with a vapour-permeable air barrier. Their vapour resistance can be very low (with the X5 air barrier Sd = 0.7 m) or it may vary in connection with relative humidity, as in the case of Intello.

In the case of wall structures the humidity-related functionality was in all cases secure, as long as rainwater had not penetrated inside the structure. In this case, the numerically modelled mould growth was not possible even with the most sensitive material, corresponding with pine wood.

If 1% of rainwater penetrates into the thermal insulation layer due to rain falling diagonally on the wall, the mould growth risk of inner elements of wind barrier increases. In all constructional cases the penetration of rainwater into the structure has involved a certain degree of mould risk, when the material on the inner surface of the wind barrier was of the most susceptible class (*very sensitive*). In this case, the impact of a vapour-permeable air barrier has proved to be a factor stimulating mould growth compared to a vapour-tight structure. Also, the amount of thermal insulation has influenced the functionality, when a porous, heat-insulating and vapour-permeable fibreboard was used as the wind barrier. In this case, the thinner thermal insulation has improved the drying and slowed down the growth of mould; however, it has not made it function in such conditions. The structures with plasterboards used as a wind barrier involved the highest mould growth risk, nor did the thermal insulation thickness bear any influence thereupon.

The cooling of the ventilation gap due to sky counter-radiation is a challenge for the functioning of the roof, when the top coat and its supporting layers do not prevent the heat transfer between the roof covering and other structures. When the structure included very sensitive materials (pine wood), the mould growth risk occurred in all the test cases with regard to the structures adjacent to the ventilation gap and the gap itself. The vapour permeability of the air barrier could be visible in certain cases; however, it was not critical for the functionality.

The possibility of using the advantages of structures filled with cellulose fibre insulations is associated with the humidity control of the fluctuating climate conditions. A structure passing moisture in both directions in a controlled manner and a hygroscopic insulation bring about self-evident advantages in situations, where the drying of the building structure should also periodically take place towards indoor air. This was visible, e.g. in the simulations of summertime exposure compared to the humidity levels on the different sides of the vapour/air barrier.

The humidity-related interaction between the indoor air and structures helps maintain good thermal comfort of the interiors. In the case of exposure of indoor air to moisture, the structure's heat losses may decrease thanks to the moisture liquefying in the structure. The duration of this phenomenon depends on the time of exposure, outdoor air conditions, properties of the inner hygroscopic materials, their conditions at the beginning of exposure and inner surface vapour resistance. In the exemplary scenario simulated for the beginning of October, after a step change, the heat current could remain positive for several days instead of generating heat loss.

The dynamic usage of the various hygroscopic material layers, such as cellulose fibre insulation in the various climate conditions and environments is a challenge and an opportunity. This will be catered for in the ongoing research project focusing on different operating conditions.