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Timber-framed exterior walls insulated with wood shavings: A field study in a nordic climate

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ABSTRACT

Wood processing residues provide a possibility to produce thermal insulation material with low environmental impact. This paper deals with the hygrothermal performance of timber-framed exterior walls with wood shavings as insulation material. The presented study consisted of field measurements of five exterior wall structures with two different types of wood shavings insulation and three reference walls. The study was performed in cold Nordic climate, where hygrothermal conditions at outer parts of a wall structure are critical. Untreated wood shavings and wood shavings coated with pulverized clay were compared as insulation materials. Different wind barriers as well as a water vapour barrier and sheathing acting as vapour retarder were also used. Results indicated no suitable conditions for mould growth inside any wall. The thermal resistance of wind barriers as well as the clay-coating of wood shavings had positive effect on the hygrothermal performance of the test walls. Wood shavings proved to be suitable insulation materials for well-insulated structures from the hygrothermal point of view, when the overall design, construction and maintenance are carried out in a proper way.

1. Introduction

1.1. Background of the study

Climate change and over-consumption of natural resources enforce using renewable building materials with low carbon footprint. Both legislation and public opinion push the building and construction sector to use sustainable products and implement very energy-efficient buildings. Utilization of wood processing residues offers one possibility to produce thermal insulation material with considerably low environmental impact [1]. This is an especially attractive alternative in countries with large, sustainably managed forest resources like Nordic countries. Because wood shavings insulation is made by collecting the residues of wood processing, it is also an economically attractive option [2,3].

The hygrothermal performance and overall suitability of all materials should be tested in the climate conditions where they will be used, studying both material properties and the performance of shell structures. In the Nordic climate, main challenges arise from heating energy savings as well as avoiding condensation and mould growth in the outer parts of a building shell. During the long heating season, the absolute humidity (g/m^3) is higher indoors than outdoors, causing moisture flow through the building shell. Therefore, the moisture flow must be restricted by a vapour barrier or vapour retarder near the warm (interior) side of the structure. The material layer(s) on the exterior side of the thermal insulation should be permeable to water vapour. This enables built-in moisture, minor rainwater leaks, moisture flow via defects of the vapour barrier, etc. to dry out. Most wind barrier products have high water vapour resistance compared to batt or loose-fill thermal insulation materials. Hence, the most critical point is the interface between the wind barrier and the diffusion-open thermal insulation. The thermal resistance of a wind barrier improves the hygrothermal performance because it enables keeping the temperature behind wind barrier higher than outdoor temperature, causing the RH to decrease. Effects of the climate change must also be taken into account. The Nordic climate will become warmer and precipitation will increase in the future [4,5], increasing the risk of mould growth. As an organic material, untreated wood shavings insulation is particularly sensitive to mould growth.

1.2. Previous studies of wall assemblies

Hygrothermal performance of exterior timber-framed walls in cold climate have been researched by field studies, laboratory measurements

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and simulations Although few studies deal with thick insulation made of wood residue, the hygrothermal behaviour of timber-framed exterior walls is rather well-known in general. Table 1 contains data for several studies of timber-framed exterior wall structures.

There were certain regularities in the results of the studies presented in Table 1. Even the wall structures with thick thermal insulation performed well, when certain criteria were met. In well-performing structures, there was no air leakage or built-up moisture. Wind barrier with a considerable thermal resistance had a positive effect. On the other hand, the walls with thick insulation dried slowly if there was any extra moisture. Hygroscopic insulation was able to absorb certain amount of moisture and was considered as preferred.

1.3. Previous material studies

According to a literature study, material density has an essential effect on the hygrothermal properties of wood residue materials, including wood shavings. Sufficient material density is essential for preventing insulation to slump and thereby causing air voids within insulation space. However, this may require material density above the optimum for thermal insulation. According to previous studies [18–20], lowest thermal conductivity values were achieved with material densities under 100 kg/m^3. Still, thermal conductivity did not increase dramatically when density exceeded 100 kg/m^3, indicating that a wide density range could be applied. Besides, the shape and thickness of wood shavings also have a considerable influence on thermal conductivity [21,22]. According to hot-box tests of Sekino et al. [23], a distinctive thermal storage effect was noticed when an insulation density of 100 kg/m^3 was used. The previously mentioned studies indicate that dry densities between 100 and 120 kg/m^3 would be optimal. Although lower values could provide an even lower thermal conductivity, the thermal capacity of relatively high density provides an attractive measure to balance short-term temperature fluctuations. Besides, the higher the density, the more moisture capacity is achieved. Because of the open-pore structure of wood shavings insulation, wood shavings can be classified as diffusion-open material, diffusion resistance factors (μ-values) being approx. between 2.5 and 9 [2,24,25]. Separate vapour/air barrier as well as wind barrier shall be applied in external wall structures.

Vulnerability to fire is obviously one major weakness of wood shavings insulation. Sensitivity to ignition can be decreased by mixing clay with wood shavings insulation [1]. Clay material also reacts with certain harmful substances [26,27], which is expected to enable clay-treated products to inhibit growth of harmful microbes. Because an unburned clay does not need energy-intensive processing when used as a construction material, it has a small environmental impact.

1.4. Research aims

The purpose of the present study was to investigate the use of building materials with low environmental impact. Use of wood-based and clay-based materials were studied. Hygrothermal performance of wooden-frame exterior walls with wood shavings insulation was a key issue. A full-scale field study of various well-insulated timber-frame structures was chosen as a research method. An essential question was whether there were favourable conditions to mould growth within these structures or not.

Besides untreated wood shavings, also clay-coated wood shavings were also used as insulation material. Clay has been used to improve fire properties of wood shavings and inhibit mould growth without using synthetic or hazardous substances. An experimental wind barrier material made of clay and wood shavings was also used in one wall to broaden the range of test materials with low environmental impact.

The effects of different wind barriers were of paramount interest. Especially temperature and moisture content in the interface between the wind barrier and thermal insulation were studied thoroughly. The effect of the vapour-retarding layer was also a key issue.

Table 1
Previous studies of timber-framed exterior walls in temperate and cold climates.

CZ	Location	Study type	Wind barrier type and thickness	Insulation type and thickness	Vapour barrier	AL	BUM	Ref.
Dfc	Oulu, Finland	Field + sim	Rockwool 100 mm + gypsum board 9 mm	MW 250 mm	PE 0.2 mm	No	No	[6]
Cfb	Machynlleth, Wales, UK	Field	OSB 11 mm	Wood-hemp insulation 55 kg/m^3, 100 mm	PE 0,5 mm/none	No	No	[7]
Dfb	Waterloo, ON, Canada	Field + sim	SBPO	FG 140 mm/CI 241 mm/Closed-cell spray foam 184 mm [b]	PE 6-mil/none	Yes	Yes	[8, 9]
Dfb	Tallinn, Estonia	Field + sim	MW 30 mm + WFB 24 mm	CI 500 mm	PE 0.2 mm/none	No	No	[10]
Dfb	Madison, WI, USA	Field + sim	Water control membrane	FG 152 mm/CI 286 mm [b]	PE 6 mil/none			[11]
Dfb	Madison, WI, USA	Field	SBPO	FG 140 mm [b]	PE/Kraft paper	No	Yes	[12]
Dfc	Tampere, Finland	Lab + sim	Gypsum board 9 mm/WFB 25 mm/MW 30 mm	CI, MW and sawdust + wood shavings, 173 and 198 mm	PE 0.2 mm/bitumen paper	Yes	No	[13]
Dfb	Trondheim, Norway	Lab + sim	WFB 12/50 mm	Wood fibre batt 300 mm/Glass wool 300 mm	Vapour retarder foil/OSB 12 mm	Yes	No	[14]
Dfb	Trondheim, Norway	Lab	SBPO foil/WFB 12/50 mm	Wood fiber 300 mm/Glass wool 300 mm	Vapour retarder/PE 0.15 mm	No	No	[15]
Dfb	Lund, Sweden	Sim	Weather resistive barrier	MW 220 mm	Vapour barrier, Sd = 50 m	No	No	[16]
Dfb Cfb Dfc	Oslo, Norway Bergen, Norway Karasjok, Norway	Sim [a]	12 mm asphalt impregnated WFB	MW 150/250/400 mm	Sd-values of 10 m, 2 m and 0,025 m were used	No	Yes	[17]

Abbreviations:
CZ = climate zone according to Köppen-Geiger classification [4].
Study type: Field = field study, Lab = laboratory study, Sim = simulation.
Materials: WFB = wood fibre board, MW = mineral wool, PE = polyethylene, CI = cellulose insulation, FG = fiberglass, SBPO = spun bonded polyolefin wrap.
AL = existence of purpose-made air leakages in the test structures (yes/no).
BUM = existence of built-up moisture in the test structures (yes/no).
[a] Laboratory and/or field measurements were also performed to supplement the simulation study.
[b] In some cases, additional insulation layer outside water control membrane/SBPO was used. In study [11], it served both as a thermal insulation layer and vapour control measure.

2. Methods and materials

2.1. Test facilities

Eight different test walls were built and installed to the test buildings of Tampere University. The test buildings consist of a steel frame and there are six test wall openings on both sides of one building (see Fig. 1). The buildings are oriented in east-west direction and test wall openings face to north and south(see Fig. 2). All the openings are 1.25 m wide and 2.45 m high. The steel frame is highly insulated to eliminate its cold bridge effect and separate test walls from each other. The temperature and RH conditions inside the test buildings are controlled.

2.2. Climate conditions on test site

Tampere is located at the boreal climatic zone, Köppen-Geiger class Dfc [4], near the border of class Dfb. The local climate represents a continental type with considerable temperature variations between summer and winter.

The coordinates of the test building site are 61°27′N, 23°52′ E and height above sea level approximately 135 m. Terrain category on the test site is III according to standard EN 1991-1-4 Table 4.1 [28]. The test area is rather protected on all sides, mainly by trees, which helps protect the test structures from driving rain and pulverized snow.

2.3. Studied exterior walls

Sections of wall structures are shown in Fig. 3. Load-bearing structure of the studied wall assemblies consisted of a timber-frame with studs c/c 600 mm. Two types of facades were used. A wooden cladding was chosen to a base case, whereas two walls were equipped with a brick veneer. There was a 30 mm wide ventilation gap behind all facades. Wall designs E2, E4 and E6-P enabled comparison between three types of thermal insulation, namely untreated wood shavings, clay-coated wood shavings and mineral wool. Wall designs E1 and W5 also enabled comparison between untreated wood shavings and mineral wool but having brick veneer instead of external cladding and gypsum board wind barrier. The effect of wind barrier was compared with walls E3-S, E3-V and E4, all insulated with untreated wood shavings. Another comparison between different wind barriers could be done with walls E6-P and E6-V having mineral wood insulation.

Walls E6-P and E6-V were added to the measurement program after two years, when reference walls insulated with mineral wool and having thermal resistance similar to the walls E1-E4 were considered useful.

The wall structures were prefabricated in a shop. The size of one prefabricated wall panel was 1,2 m in width and 2,4 m in height. Wood shavings insulation was installed by a blowing machine. Wall panels were in horizontal position during the blowing.

Materials used in the test walls were commercially available products which are widely used in Finland. The clay-coated wood shavings insulation and the wind barrier made of mixture of clay and wood shavings were exceptions. The properties of these products were measured at Tampere University of Technology. Material properties are presented in Table 2. Water vapour permeabilities have been measured by wet cup test applying standard ISO 12572:2016 [29], thermal conductivities by heat flow meter apparatus according to standard EN 12667:2001 [30] and air permeabilities by static airflow method with pressure differences ranging from 0 to 50 Pa according to standard EN ISO 9053–1:2018 [31].

Wood shavings used in the study were by-products of timber planing. The timber was kiln-dried before planing which eliminated the risk of mould growth when storing the material prior to use. The shavings were sieved after planing to select a suitable particle size. The average thickness of a single particle was approx. 0,1 mm. The width and length of the particles varied. Maximum width and length were approx. 6 mm and 20 mm. Shavings were mostly made of Scots pine *(Pinus sylvestris)*. Because this species together with European spruce *(Picea abies)* dominate the Finnish forest industry and are often handled on the same production lines, there were possibly some portion of European spruce included. Air volume fraction was calculated based on the average

Fig. 2. View of test building 2 and surrounding terrain.

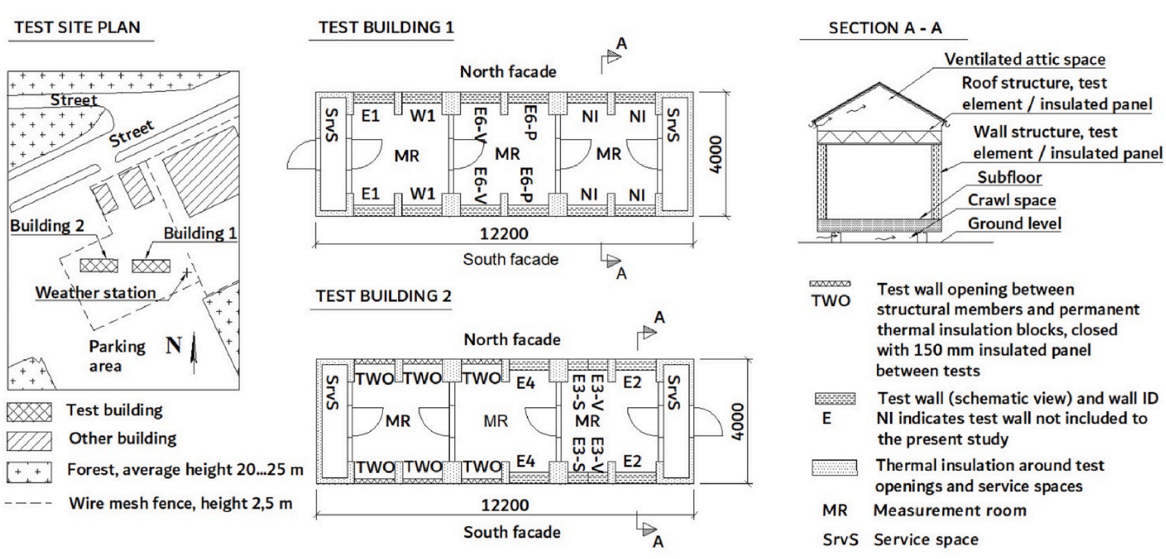
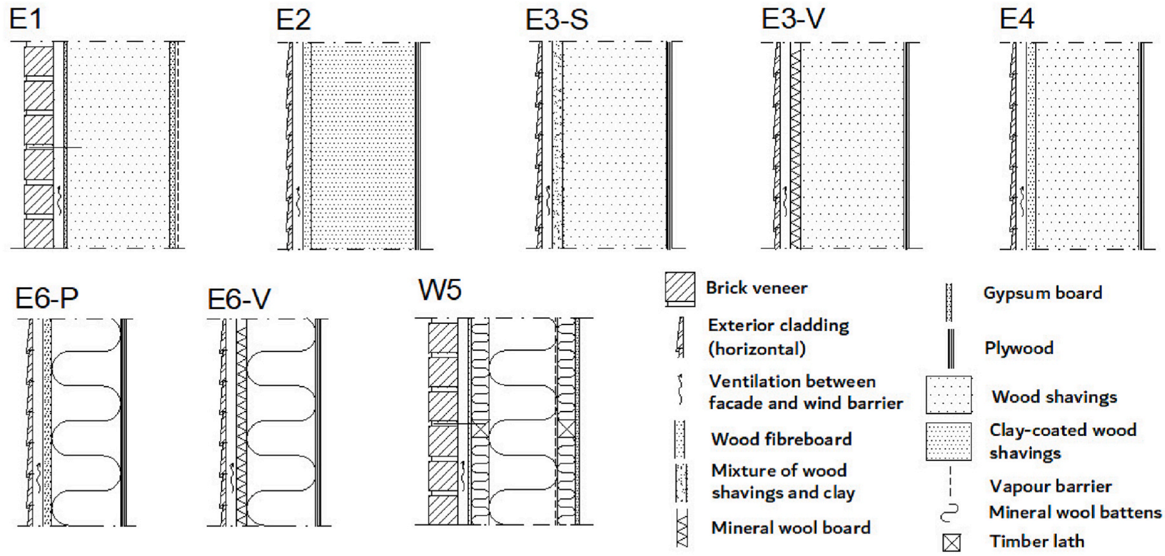


Fig. 1. Test buildings and situation of test walls.



Wall ID	Material layers					U-value (W/m^2K)
	Facade	Wind barrier	Thermal insulation	Interior sheathing	Vapour barrier	
E1	Brick veneer 85 mm	Gypsum board 9 mm	Wood shavings 300 mm	Plywood 15 mm	PE plastic foil 0.2 mm	0.18
E2	Horizontal cladding	Wood fibre board 25 mm	Clay-coated wood shavings 300 mm	Plywood 15 mm	none	0.19
E3-S	Horizontal cladding	Mixture of wood shavings and clay 30 mm	Wood shavings 300 mm	Plywood 15 mm	none	0.21
E3-V	Horizontal cladding	Mineral wool 30 mm	Wood shavings 300 mm	Plywood 15 mm	none	0.18
E4	Horizontal cladding	Wood fibre board 25 mm	Wood shavings 300 mm	Plywood 15 mm	none	0.19
E6-P	Horizontal cladding	Wood fibre board 25 mm	Mineral wool 200 mm	Plywood 15 mm	none	0.21
E6-V	Horizontal cladding	Mineral wool 30 mm	Mineral wool 200 mm	Plywood 15 mm	none	0.19
W5	Brick veneer 85 mm	Gypsum board 9 mm	Mineral wool 50 + 200 + 50 mm	Gypsum board 13 mm	PE plastic foil 0.2 mm	0.14

Fig. 3. Tested wall structures. Exterior sides on the left.

Table 2
Material properties. t = thickness, ρ = density, μ = water vapour resistance factor, λ_{10} = thermal conductivity at +10 °C, R = thermal resistance, k_a = air permeability. Underlined values according to manufacturers. Values in italics taken from literature [32,33].

Layer	Material	t (mm)	ρ (kg/m^3)	μ (–)	λ_{10} (W/mK)	R (m^2K/W)	k_a ($m^3/(msPa)$)
Wind barrier	Mineral wool board	30	90	1	0.033	0.91	$<1*10^{-5}$
	Wood fibreboard	25	280	16	0.055	0.56	$2.2*10^{-6}$
	Gypsum board	9	770	*8*	*0.23*	*0.039*	*$1.8*10^{-9}$*
	Mixture of wood shavings and clay (experimental product)	30	500	n/a	0.09	0.33	$3.0*10^{-7}$
Thermal insulation	Mineral wool batts [a)]	300	16	1	0.036	8.3	*$1.0*10^{-4}$*
	Wood shavings (without any adhesives)	300	160	1.2	0.055 [b)]	5.5	$6.4*10^{-5}$
	Clay-coated wood shavings	300	266	1.2	0.059 [b)]	5.1	$6.2*10^{-5}$
Vapour barrier	Plastic foil	0,2	*980*	10000	[c)]	*0.02*	*$4.4*10^{-7}$*
Interior lining	Plywood	15	600	*250*	*0.12*	*0.13*	*$8.3*10^{-13}$*
	Gypsum board	13	830	6	0.25	0.052	*$2.6*10^{-9}$*

[a] Three layers, 50 + 200 + 50 mm, were used. Material properties are presented for 300 mm layer.
[b] Maintained at 50 % relative humidity before measurement.
[c] Not relevant quantity for foils.

density of Scots pine, 510 kg/m^3. The air volume fraction was 0.69.

A portion of wood shavings was mixed with brick clay used as a raw material of red bricks. This was done by mixing 20 kg of wood shavings, 10 kg of clay and 10 kg of water together. The mixture was dried before installing to the test walls. The brick clay was considered suitable for coating wood shavings due to its tiny particle size, <0.002 mm, which enables even distribution of clay on the surfaces of wood shavings.

Equilibrium moisture content for both original and clay-coated wood shavings was measured in a climate chamber according to standard ISO 12571:2021 [34]. The sample densities differ from those used in the test walls, see Table 1. The difference occurred because the samples for moisture equilibrium test were scooped to the measurement vessels, whereas the test walls were insulated by blowing the insulation material to the test wall panels. The results are presented as adsorption and desorption curves in Fig. 4. The clay-coated insulation material has a little less moisture capacity as kg moisture/kg dry material than

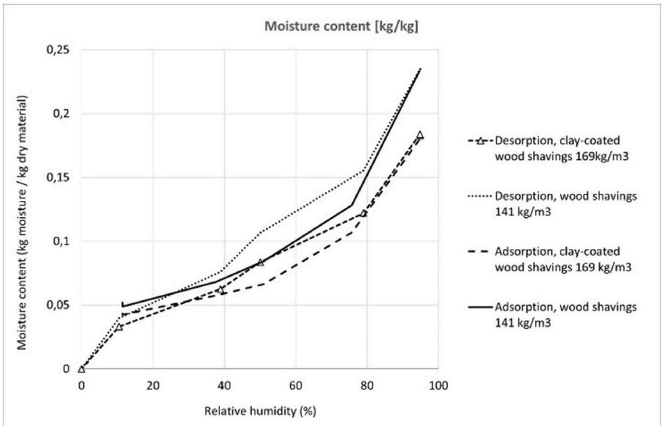


Fig. 4. Moisture equilibrium curves for original and clay-coated wood shavings as a function of relative humidity.

untreated wood shavings. Because of greater density of the former, it still has more moisture capacity per volume.

2.4. Instrumentation

Temperature, RH and heat flux values were recorded by dataloggers every 1 min. Fig. 5 indicates sensor positions inside studied walls.

RH and temperature sensors were also placed both outdoors and inside measurement rooms to monitor and control the temperature and RH inside the buildings. Sensors inside the building were located near the test walls on both the south and north façades. Solar radiation at both the south and north facades, air pressure, solar radiation, wind speed and direction, rainfall and the amount of driving rain on south façade as well as pressure differential over the building shell were also measured. All sensors were calibrated before study. Sensor types, measuring ranges and accuracies are shown in Table 3.

2.5. Boundary conditions

To simulate moisture loads in real buildings, test buildings were equipped with temperature and RH control. Indoor temperature was set to +21 °C. Internal moisture load was 5 g/m^3 when outdoor temperature was below +5 °C, and 2 g/m^3 when outdoor temperature was above +15 °C. The values between +5 °C and +15 °C were interpolated linearly. The aim was to simulate the contemporary Finnish design conditions [35]. The used moisture load values present the maximum values measured from the bedrooms and living rooms of residential buildings [36,37], but are likely to occur in apartments with high occupancy and low air ventilation rate.

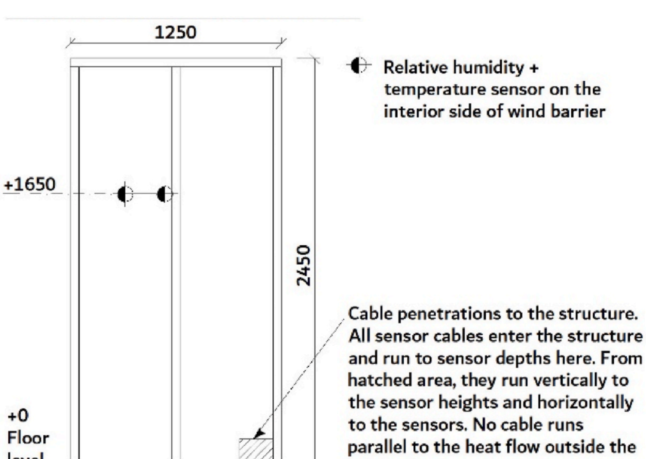


Fig. 5. Sensor layout inside the test wall, view from inside.

Table 3
Properties of sensors.

Measured variable	Sensor manufacturer and type	Measurement range	Accuracy
Surface temperature (inside)	Texas Instruments LM335A	−40 … +100 °C	±0,5 °C
Temperature and RH (inside)	Miranlink DLS-IAQ.THB	−40 … +125 °C	±0,3 °C
		0 … 100 % RH	±2,5 % RH at 20 … 80 % RH
Barometric pressure (inside)	Miranlink DLS-IAQ.THB	300 … 1100 mbar	±1,0 mbar (abs.), ±0,13 mbar (relative)
Pressure difference over building shell	Miranlink DLS-IAQ.THB-DP	±500 Pa	±3 Pa (reading accuracy), ±0,1 Pa (zero reading accuracy))
Heat flow from inside to outside	Hukseflux HFP01	−2000 … 2000 W/m2	approx. 5 %
Temperature and RH (outside)	Vaisala HMP110	0 … +40 °C, 0 … 90 % RH	±0,2 °C, ±1,5 % RH
		0 … +40 °C, 90 … 100 % RH	±0,2 °C, ±2,5 % RH
		−40 … 0 and + 40 … +80 °C, 0 … 90 % RH	±0,4 °C, ±3,0 % RH
		−40 … 0 and + 40 … +80 °C, 90 … 100 % RH	±0,4 °C, ±4,0 % RH
Wind speed and direction	Vaisala WMT703 (ultrasonic sensor)	0 … 75 m/s, 0 … 360°	±2 % or 0,1 m/s, ±2,0°
Barometric pressure	Vaisala BARO-1QML	500 … 1100 bar	±0,15 bar
Rain and driving rain	Vaisala RG13H (tipping bucket)		±2 %, when 1 l/h
Long wave radiation	Vaisala SGR3 (pyrgeometer)	4,5 … 420 μm	±15 W/m^2
Solar radiation	Vaisala SMP3 (pyranometer)	300 … 2800 nm	±5 W/m^2

2.6. Criteria for hygrothermal performance

There were two criteria for the overall performance of the studied walls. First, condensation was not allowed in any circumstances. In the Nordic climate, building shells can dry out effectively only during a few months in springtime and summertime. If condensation occurs outside this period, moisture is likely to stay in the structure for a long time, possibly causing mould and rot. Second, any favourable conditions to mould growth inside wind barrier were considered undesirable. Mould growth in thermal insulation causes a real risk for inhabitants because of the contamination risk via imperfections in vapour/air barriers and interior sheathings, e.g. via improperly sealed electrical sockets and other penetrations.

Mould risk was evaluated according to Finnish mould growth model [38–40]. The model takes into account the dynamic temperature and RH histories of the subjected material. There are four mould sensitivity classes (MSC) for materials, from 1 to 4, class 1 being the most sensitive. For example, sawn European spruce *(Picea abies)* and sawn or planed Scots pine *(Pinus sylvestris)* belong to class 1. Because these two tree species dominate Finnish timber construction, class 1 was used. The intensity of mould growth is expressed by mould growth indices from 0 to 6 [38,39]. Fig. 6 illustrates the significance of temperature and relative humidity for the development of mould index.

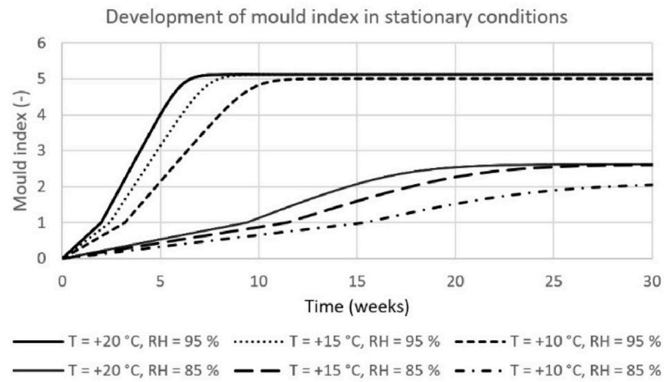


Fig. 6. Development and maximum values in certain conditions with the material of mould sensitivity class 1.

Mould indices were calculated using MS Excel using measured temperature and relative humidity values. Mould indices over 1,0 were considered as undesirable in this study.

2.7. Test period

To monitor the hygrothermal performance during all seasons, the length of the test period was roughly two and half years. The test period began on 23rd September 2020, apart from the structures E6-P and E6-V which were measured from 26th July 2022 on. The test period was finished on 16th November 2022. The test period included three critical periods which occur during late summer and autumn.

The short measurement period of walls E6-P and E6-V shall be noted. Because the walls were prefabricated in sheltered shop conditions, they did not contain any extra moisture. The moisture capacity of dry wood-based parts, especially timber-frame and wood fibre board wind barrier, may have been profitable during the measurement period on autumn 2022.

3. Results

3.1. Determination of the analysis periods

In the Nordic climate, favourable conditions for mould growth occur mostly in late summer and autumn. Occurrence of critical period varies year by year, depending on the normal variations of weather conditions. In this study, the beginning of these period was defined according to Equation (1), using measured data behind wind barrier:

$$RH_{crit} - RH_{meas} < 5 \text{ \%-units} \qquad \text{Equation 1}$$

where

RH_{crit} = relative humidity value where mould growth is possible, calculated according to measured temperature using mould sensitivity class 1 [40] [%-units]
RH_{meas} = measured relative humidity [%-units]

The critical period was declared to begin while the condition of Equation (1) was fulfilled first time behind wind barrier in any of the studied structures. The limit of 5 %-units has been determined experimentally and is more or less arbitrary. Some margin of safety was still considered justified. When the difference between RH_{crit} and RH_{meas} is 5 %-units in a reference spot, the RH might be very close to RH_{crit} in some other part of test wall, due to uneven temperature and RH distributions and sensor inaccuracies. An unambiguous criterion was found necessary to determine the define the beginning of a critical period. The criteria of Equation (1) recognize the increase of outdoor RH on the late summer and autumn, as well as the decrease of temperature on late autumn. The former provides conditions for the beginning of mould growth, whereas the latter causes mould growth to decrease. The hygrothermal conditions tend to change challenging for shell structures once the condition has been met after the summer period. The critical period was over while the condition of Equation (1) was not met in the following four weeks. The four-week period has adopted because the temperatures can vary considerably on the late autumn. Even a week-long period with sub-zero temperature can be followed by rather warm period which enables the mould growth again. The criteria of four weeks ensured that temperatures were constantly near or below zero which absolutely eliminated the risk of mould growth. The start and end dates and duration of critical periods as well as temperature and relative humidity conditions during these periods are listed in Table 4.

The use of the critical period helps analysing the hygrothermal performance of the structures. For example, the temperature extremes which occur during winter and midsummer do not interfere the results. High wintertime RH values behind wind barrier are normal because the outdoor RH tends to be high during Nordic winter. Condensation behind a wind barrier in sub-zero temperatures is a possible scenario in the Nordic climate but it must be analysed separately. Because the studied structures were constructed for experimental use and built with care, there was no obvious risk of air leakage from the inside into the wall assemblies.

Outdoor temperatures and relative humidities during critical periods are shown in Figs. 7 and 8.

Table 4 and Figs. 7 and 8 reveal differences between outdoor conditions of various years. Exceptionally warm period in year 2022, ranging from approx. between 8 and 28 August, stands out. This period was preceded by a few humid days.

3.2. Effect of thermal insulation

The difference between hygroscopic and non-hygroscopic thermal insulations can be clearly seen by comparing the walls E2, E4 and E6-P with each other, as well as the walls E3-V and E6-V with each other. There were clear differences between RH averages, but not temperature averages. The RH averages during autumn 2022, on the north façade in the middle of studs, were 64.6 %, 67.7 % and 69.9 % for the walls E2, E4 and E6-P, 65.6 % for E3-V and 67.8 % for E6-V (see Fig. 9). In other words, RH averages were considerably lower with walls having hygroscopic wood shavings insulation (E2, E4 and E3-V), than with walls insulated by non-hygroscopic mineral wool. This reveals the beneficial effect of moisture buffer capacity of hygroscopic insulation. The results measured from south façade, in the middle of the cavity and next to the stud (Figs. 10 and 12) confirmed the results. On the north façade, next to the stud, most of the RH averages were very near each other (Fig. 11).

The third comparison between hygroscopic and non-hygroscopic insulation material was performed between the walls E1 and W5. Yearly RH averages of the former were from 5 to 10 %-units lower than the latter, see Figs. 9–12. However, differences between thermal resistance values of the two walls may have been a dominating factor.

The comparison between walls E2 and E4, insulated with clay-coated and untreated wood shavings, indicated the good performance of clay-

Table 4
Critical periods during the test. Avg = average, Std = standard deviation.

Year	Start date of critical period	End date of critical period	Duration of critical period [days]	Outdoor temperature		Outdoor RH	
				Avg [°C]	Std [°C]	Avg [%]	Std [%]
2020	23rd August	24th December	123	6,4	6,1	90,0	12,6
2021	8th August	19th November	103	8,6	5,2	88,6	12,2
2022	26th July	16th November	113	10,7	6,5	85,7	15,7

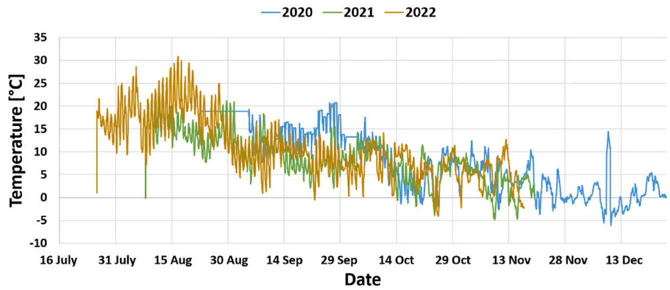


Fig. 7. Outdoor temperatures during critical periods.

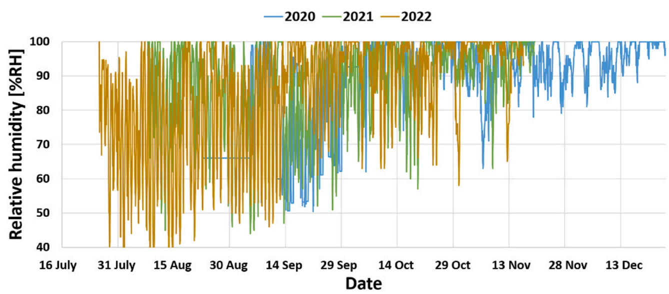


Fig. 8. Outdoor relative humidities during critical periods.

coated wood shavings insulation. Because the RH averages of the former were considerably low on the south façade, larger density and hence larger thermal capacity of clay-coated wood shavings insulation may have affected the results. The exact explanation for the difference between the two insulation materials requires further studies.

3.3. Effect of wind barrier

The wind barrier type had a clear effect on both temperature and RH values. This was particularly clear with walls E3-S, E3-V and E4. The lowest temperature values for the whole study were recorded for structure E3-S having the experimental wind barrier made of wood shavings and clay. Even in this structure, RH values remained low enough considering the proper hygrothermal performance. Favourable circumstances for mould growth prevailed only occasionally. The highest RH readings were recorded in 2020 on the north façade, in the middle of studs. RH averages were 75.6 %, 74.1 % and 66.9 % for walls E3-S, E4 and E3-V, respectively (see Fig. 9). The results were similar in 2021 and 2022, although the RH levels were lower in general. In other orientations and sensor positions the results of E3-S and E4 were somewhat inconsistent, whereas the wall with mineral wool wind barrier performed very well in all cases, see Figs. 10–12.

The comparison between the walls E6-P and E6-V also demonstrated differences between the wood fibre board and mineral wool wind barriers, although the RH differences were rather small, 2.2 %-units on the autumn 2022 (north façade, in the middle of the studs, see Fig. 9).

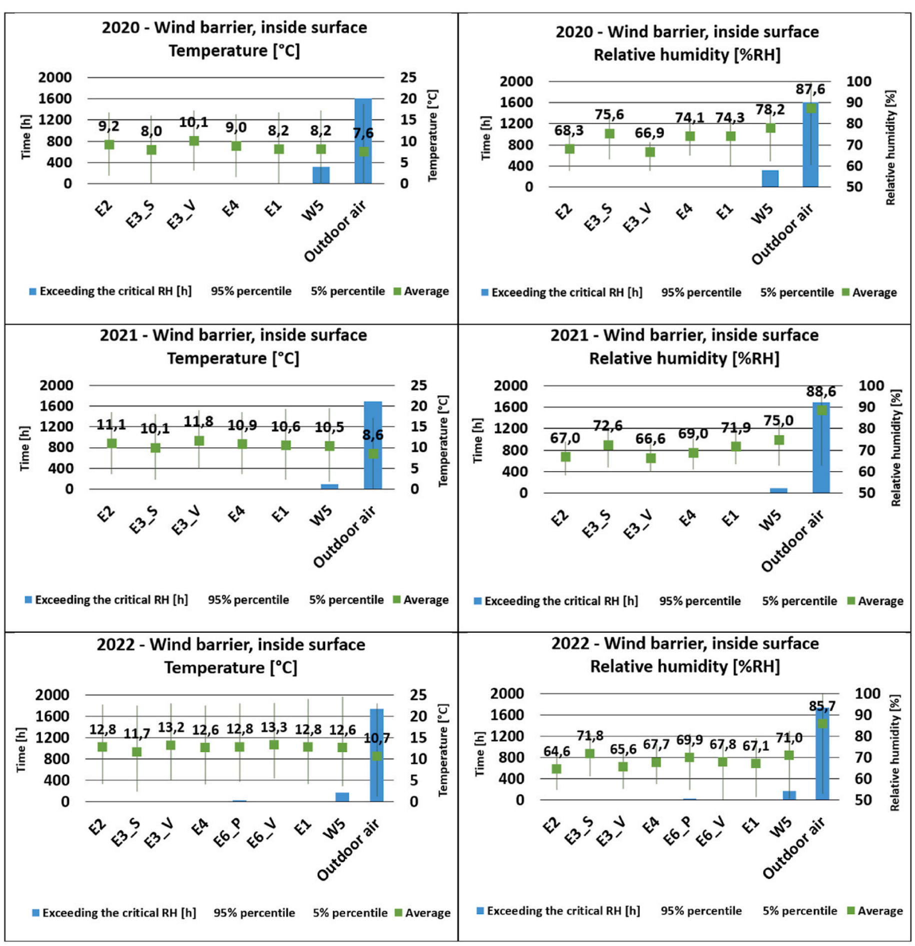


Fig. 9. Temperature and relative humidity averages behind the wind barrier from the north façade in the middle of the cavity, as far from the timber parts as possible. T./RH scale on the right side of each bar chart. 95 % and 5 % percentiles for T/RH values are indicated as vertical bars. Blue bars indicate the number of hours while favourable conditions for mould growth have prevailed. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

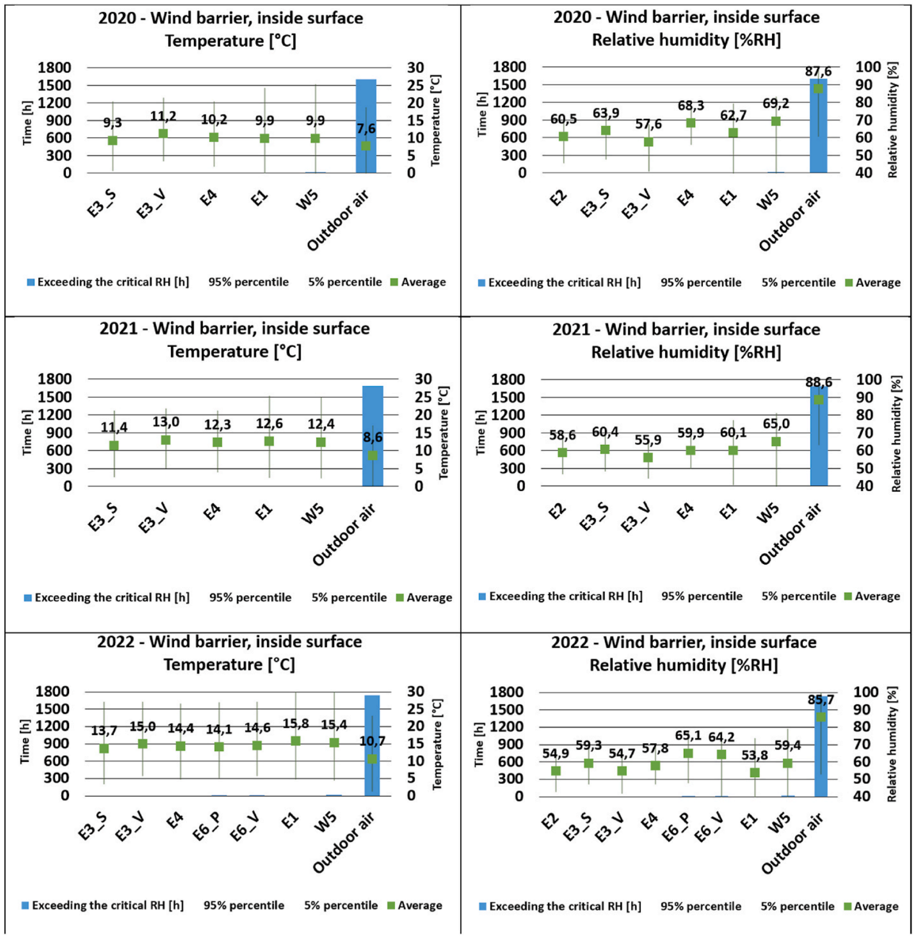


Fig. 10. Temperature and relative humidity averages behind the wind barrier from the south façade in the middle of the cavity, as far from the timber parts as possible. T/RH scale on the right side of each bar chart. 95 % and 5 % percentiles for T/RH values are indicated as vertical bars. Blue bars indicate the number of hours while favourable conditions for mould growth have prevailed. Temperature data from wall E2 has been omitted because of sensor malfunction. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

The decent performance of gypsum board wind barrier of E1 was a positive result, although the RH values were higher than the other walls insulated with wood shavings (except E3-S). The hygrothermal performance of the gypsum board wind barrier was questioned before the study, because of the thermal resistance of the product is poor. Although the different façade materials make an exact comparison between E1 and other walls with wood shavings insulation impossible, the acceptable performance of E1 was an important observation.

In general, the higher temperature values, the lower RH values were recorded, and vice versa. Structure E2, which had a wood fibreboard wind barrier and clay-coated wood shavings thermal insulation, was an exception. Despite of its wind barrier product, it achieved lowest average RH values together with structure E3-V which was equipped with a mineral wool wind barrier and wood shavings insulation.

3.4. Effect of orientation and façade type

Solar radiation on the south façade caused low RH values compared to the north façade. RH values were approximately 10 %-unit lower than on the north façade. The similar phenomenon was observed both in the middle of cavity and next to the timber stud, see Figs. 9–12.

The most interesting results were relatively low RH values of walls with brick cladding, E1 and W5, on the south facade The reason must lie in the protected test site and eaves of the test buildings. This obviously prevents the massive driving rain hitting the south façade, which is a common problem in Finland. On the north façade, the facade type had no significant effect, see Fig. 9. Temperature values for the two walls with brick veneer, E1 and W5, were also near each other.

3.5. Effect of sensor position

Thermal conductivity of solid wood used in timber-frames is roughly twice the thermal conductivity of wood shavings insulation. This was assumed to have a distinctive effect to the temperature and moisture distribution inside the structure.

Temperatures next to the studs were generally somewhat higher or like the temperatures between the studs. Hence, the most critical conditions were met between the timber studs. Distance from the stud has the largest effect in the case of wind barrier made of clay – wood shavings mixture, wall E3-S. On the other hand, temperatures behind the mineral wool wind barrier were almost equal whether the measurement point was next to the stud or between studs. Temperature readings of E1 and W5 having brick veneer were also near each other, whether measured next to the stud or between studs. Fig. 11 displays the average temperature and RH conditions behind the wind barrier, next to the timber framing, on the north façade. RH data from wall E1, as well as temperature data from wall E3-V from the year 2020, has been omitted because of sensor malfunction.

On the south façade, proximity of a stud reduced differences between different walls as it did on the north façade (Fig. 12). When a wall was equipped with a mineral wool wind barrier, temperatures were very near those measured between the studs (Fig. 10). On the other end, a

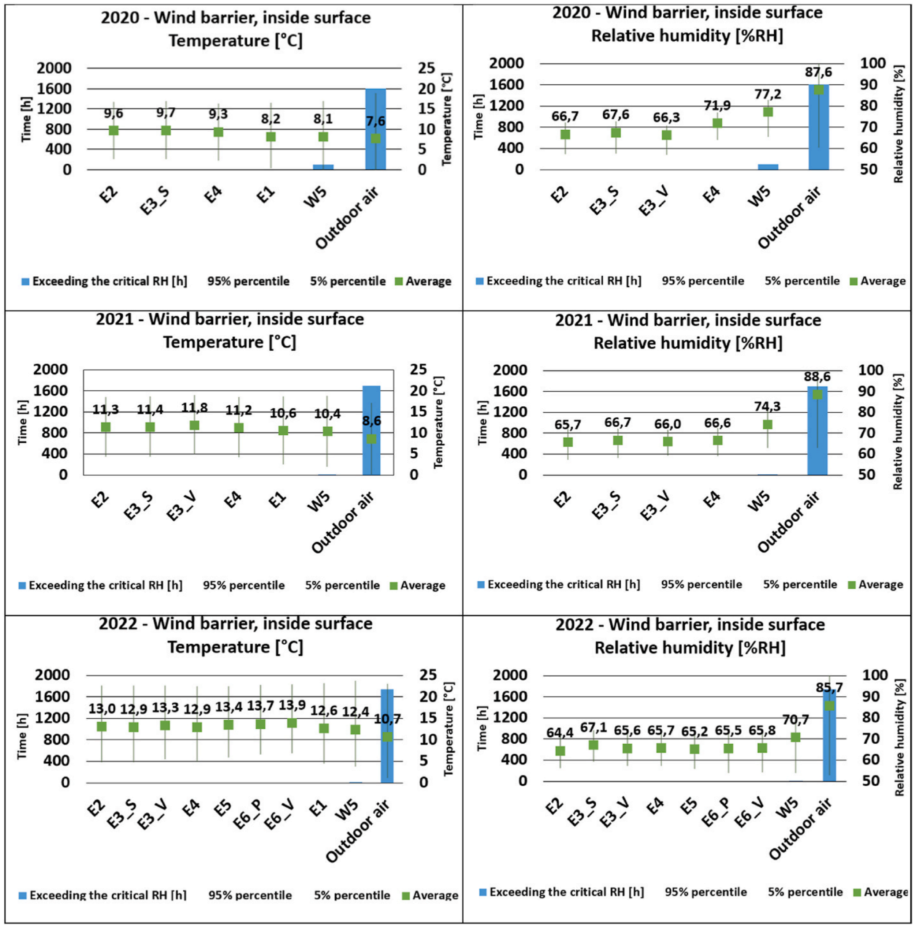


Fig. 11. Temperature and relative humidity averages behind the wind barrier from the north façade next to the timber stud. T/RH scale on the right side of each bar chart. 95 % and 5 % percentiles for T/RH values are indicated as vertical bars. Blue bars indicate the number of hours while favourable conditions for mould growth have prevailed. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

considerable temperature difference occurred in the wall E3-S having a wind barrier made of clay and wood shavings. The results are coherent with those obtained between studs, see Figs. 9 and 11.

3.6. Risk of mould growth behind the wind barrier

To further demonstrate the hygrothermal performance of different structures, the data from the wall W5 was analysed further. This wall experienced more suitable conditions for mould growth than any other, see Figs. 9–12. Analysis was made on the north façade, between studs. On the south façade, relative humidity levels were clearly lower than on the north façade. Hence, the analysis represent the worst-case situation for all the analysed structures.

Hygrothermal conditions behind the wind barrier are presented as temperature and RH curves in Fig. 13 and as isopleth chart in Fig. 14. Fig. 13 presents temperature and RH during the critical period of year 2020, which was the most challenging period during the study. In Fig. 14, single measurement results are expressed as dots, each dot representing one temperature – RH value pair. There is also a limit curve for material which belongs to mould sensitivity class 1. The positions of the dot clouds demonstrate the performance of structures. When there are no measurement points above the limit curve, there is absolutely no risk for mould growth. The more points appear above the limit curve, the more doubtful the performance of a particular wall is. On temperature range of +6 … +17 °C, conditions exceeded critical limit regularly, as Figs. 13 and 14 indicate. Although the calculated mould growth risk was well below 1, annual weather variations and climate change can easily change the situation.

One positive result was the absence of very high RH levels at sub-zero temperatures. No RH values over 85 % were measured there. This indicated non-existent condensation risk behind wind barrier at sub-zero temperatures. In such conditions, condensation would cause ice formation. Various problems could occur after the temperature rise and melting of ice.

3.7. Moisture flow by diffusion

Moisture flow from indoors to outdoors by diffusion and convection did not have significant effect in any wall. This was expected because of the sufficient water vapour resistances of the interior layers and permeable wind barriers. The water vapour permeability of wind barriers was at least tenfold compared to interior plywood sheathing of structures E2, E3-S, E3-V and E4. In structures W5 and E1, the difference between vapour barrier and wind barrier is even greater.

3.8. Weather conditions during measurement period

Weather conditions occurred during the study were considerably easier than climatological test reference years used in Finland [41]. No exceptional conditions or phenomena were observed. However, because both relatively cold (near −20 °C) and warm (approx. +30 °C) temperatures were recorded, hygrothermal performance of test structures could be observed on a wide temperature range.

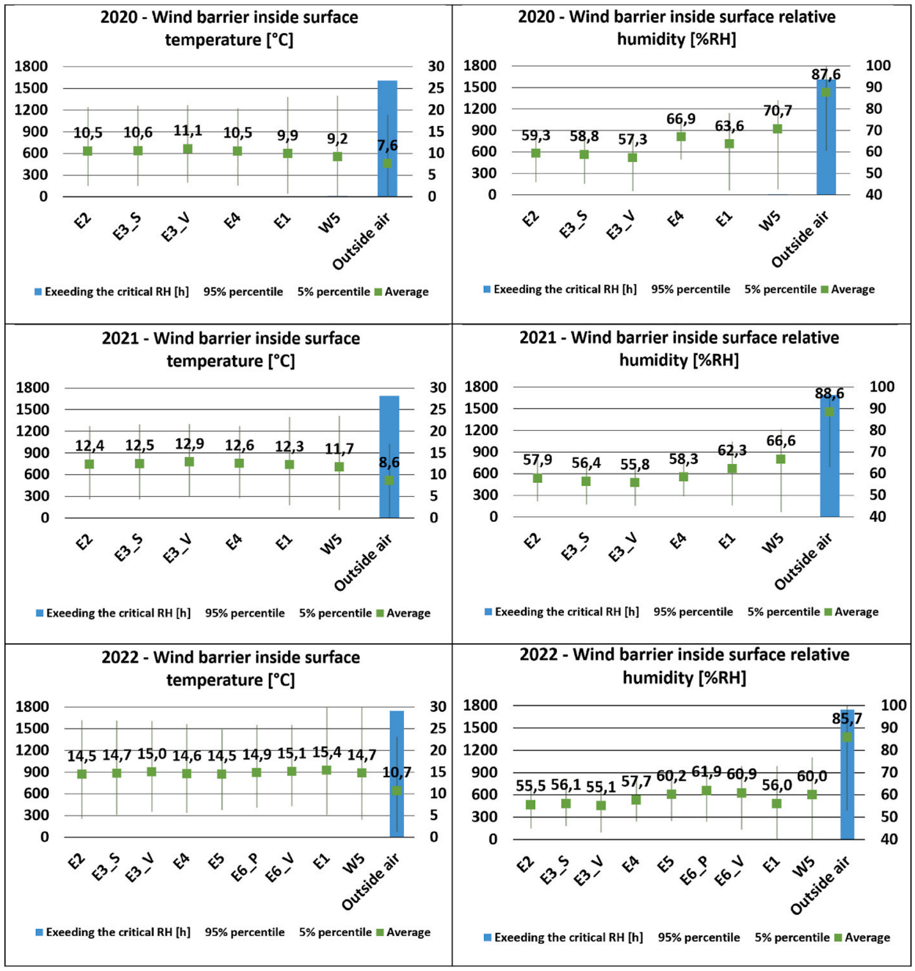


Fig. 12. Temperature and relative humidity averages behind the wind barrier from the south façade next to the timber stud. T/RH scale on the right side of each bar chart. 95 % and 5 % percentiles for T/RH values are indicated as vertical bars. Blue bars indicate the number of hours while favourable conditions for mould growth have prevailed. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

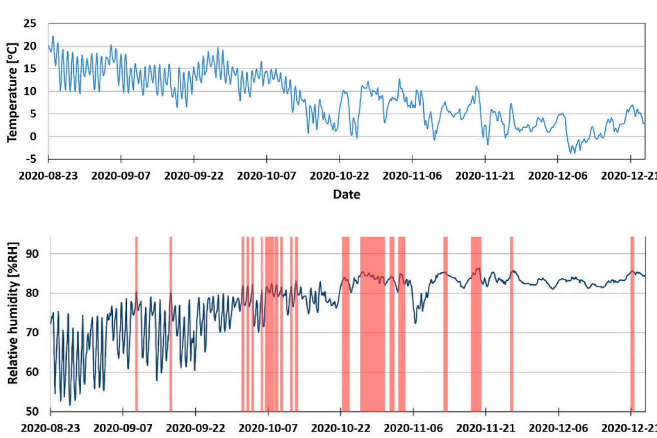


Fig. 13. Temperature and relative humidity behind wind barrier of wall W5 during autumn 2020. Red bars indicate the periods when mould growth is possible. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

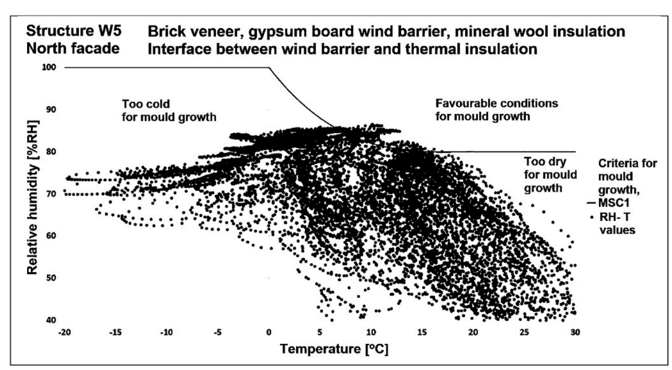


Fig. 14. Accumulation of temperature and relative humidity value pairs for a one year test period.

4. Discussion

4.1. Hygrothermal performance of structures

The primary purpose of the present research was to investigate the use of wood shavings as an insulation material. Three insulation products were studied: wood shavings without any modifications and wood shavings with clay coating. There was also an experimental wind barrier product made of mixture of wood shavings and clay. Several wall assemblies were tested in a field study for at least one year to compare the hygrothermal performance of all of the products exposed to the Nordic climate conditions. All the walls had a satisfactory or even good R-value considering energy savings. On the other hand, various studies have demonstrated the negative effects of thick insulation layers, namely slow dry-out after moisture leaks and more favourable conditions for mould growth. The negative influences stand out especially when the overall design of a wall assembly is not optimal [8,10,12,16].

According to this study, no chemical treatment of wood shavings insulation is required for preventing mould growth. All the studied wall structures fulfilled the criteria set in Chapter 2.6, namely the absence of favourable conditions for mould growth and condensation. However, there were considerable differences between various structures. The most promising materials were the clay-coated wood shavings insulation and the mineral wool wind barrier. The combination of these two materials could perform even better than any structure tested in this study.

4.2. Significance of wind barrier

The effect of the wind barrier was clearly detected by comparing walls E3-S, E3-V and E4 which were identical in other ways. The greater the thermal resistance of the wind barrier, the better the hygrothermal performance of the structure was. This agrees with earlier studies [10, 14] despite of the different thermal insulation materials used in these studies. All of the studied wind barriers had a relatively high water vapour permeability, which enables the drying of the structures by diffusion. Despite this, the modest hygrothermal performance of wall E3-S, compared with other walls, was a disappointment.

Choosing the optimal wind barrier product for a real construction project is a rather conflicting issue. For example, gypsum board has many good properties, but also a low thermal resistance. One solution, although rather expensive, is the use of a mineral wool board outside a sheet material [11].

4.3. Hygrothermal performance of untreated vs. clay-coated wood shavings insulation

The difference between untreated and clay-coated wood shavings insulation was clear and somewhat unexpected. Use of clay-coated insulation in wall E2 caused considerably lower RH levels than untreated insulation in wall E4, see Figs. 8–11. There are two possible reasons. First, greater density of clay-coated insulation means greater thermal and moisture capacity compared to untreated insulation. This is likely to balance the temperature and moisture fluctuations, especially the extreme values. Second, the somewhat higher thermal conductivity value of clay-coated insulation causes slightly higher thermal transmittance value of insulation layer of wall E2. Therefore, heat flow through the structure is larger which rises temperature in outer parts of the structure, especially behind wind barrier.

4.4. Suggestions for further studies

The study could be enhanced by hygrothermal simulations. The simulation models could be calibrated against the measured data. Necessary material data is already available. The simulations should be done using a 3D simulation program. This enables including all the components of timber frame to the model. Moreover, the use of 3D program enables the simulation of various junctions. Basement and corner junctions, for example, include cold bridges which may cause problems in building applications. Effects of future climate should absolutely be simulated. This enables the promotion of wall solutions which perform flawless even in the future climate.

5. Conclusions

This work focused on the hygrothermal performance of well-insulated timber-framed structures with wood shavings insulation. Several wall assemblies with different insulation materials, wind barriers, façades and interior sheathings were attached to the external wall of test building for more than one year.

Both untreated and clay-coated wood shavings insulation materials performed well. No condensation was detected and there were no favourable conditions for mould growth inside the wall structures. Hence, wood shavings insulation can be used as insulation material in wall structures with relatively high thermal resistance values. The clay-coated insulation materials performed even better than the untreated. The reasons are under investigation. However, the difference between clay-coated wood shavings and the two other insulation materials was clear: higher density resulting in higher thermal and moisture capacity. In general, constructions with well-performing material combinations should be applied in practice. Previous studies have demonstrated considerable differences in the hygrothermal performance between different walls with e.g. almost equal thermal transmittance value [9–11].

A wind barrier with adequate thermal resistance and water vapour permeability was once again proved to be necessary. Considering the interior sides of the wall structures, both the vapour barrier and interior sheathing with vapour retarding properties performed well in this study.

One purpose of this study was to demonstrate the performance of organic, renewable building materials with low ecological impact. These materials may, however, perform especially well when combined with non-organic building materials. The well-performing test structure E3-V with a mineral wool wind barrier is an example. This underlines two points. First, renewable building materials and other materials may form an extraordinary combination when all materials are used properly. Second, it makes using e.g. wood shavings possible in many applications, both in new and old buildings.

The studied façade solutions and detailing were of rather typical ones used in Finland. Because the test site was rather protected and the test building were low, the test conditions were not harsh. Harsher conditions will occur, for example, on coastal areas or on top of multi-storey buildings. All reasonable measures to prevent water leaks should be used because wood shavings, as organic material, are sensitive to mould growth and drying times are expected to be long. The same concerns moisture loads from the inside. Both diffusion or convection paths should be obstructed by using proper material layers with robust details and done by good workmanship.

Further field or laboratory studies in different climate conditions and with various combinations of material layers are highly recommended before using wood shavings insulation in different climate conditions and/or with different material combinations than used in this study. Further studies of structures with clay-coated wood shavings are especially worthwhile because of the promising results achieved in this study.

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CRediT authorship contribution statement

Jaakko Hietikko: Writing – review & editing, Resources, Investigation, Formal analysis. **Eero Tuominen:** Supervision, Resources, Methodology. **Ilkka Valovirta:** Writing – original draft, Visualization. **Juha Vinha:** Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgement

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