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Advancing Timber for the Future Built Environment

ASSESSMENT OF HYGROTHERMAL PERFORMANCE OF TRADITIONAL AND INSULATED CORDWOOD MASONRY

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ABSTRACT: Cordwood masonry is a traditional building method using wood logs mortared with clay, oriented with the fibre direction perpendicularly to the wall's length. This technique, using affordable and low emission materials, supports circularity through timber reuse and design for disassembly. In this study, experimental investigation of the hygrothermal performance of a cordwood wall has been conducted in a laboratory. In particular, the U-value of a cordwood wall was measured experimentally and compared with theoretical calculations. The risk for mould growth in both traditional (uninsulated) and insulated cordwood walls was examined with validated numerical simulations. The results show that a traditional cordwood wall is poorly insulated and effectively dissipates moisture, making it suitable for structures like cabins and sheds with less demanding energy efficiency requirements. Furthermore, an externally insulated cordwood wall without a vapour retarder is highly vapour-permeable and could potentially be used in buildings with low indoor moisture levels. On the other hand, an externally insulated cordwood wall with a vapour retarder can withstand mould growth even with higher indoor moisture levels, making it suitable for use in contemporary building designs.

KEYWORDS: cordwood masonry, clay, thermal transmission, mould growth, natural building

1 INTRODUCTION

Historical construction techniques have often been sustainable and circular, effectively utilizing materials and reuse. Preserving, understanding, and further developing these methods can help the industry's shift toward sustainability, as the Norwegian Museum of Cultural History (Norsk Folkemuseum) focuses on in the Tradlab TRE project in Oslo. As a FutureBuilt innovation pilot, Tradlab TRE promotes historical and natural building methods using reclaimed timber, including the traditional timber frame of externally insulated cordwood masonry. The construction project will be realized during 2025, using local clay from the construction site for the cordwood masonry. Once the building is in use, indoor humidity levels, carbon dioxide levels and energy consumption will be monitored.

This study broadly investigates the building physical aspects of the cordwood wall, specifically thermal performance, heat and moisture transport, and mould growth risk. The paper presents the main findings from a series of laboratory experiments and validated hygrothermal numerical simulations. It provides the measured U-value of a cordwood wall and compares it to the expected U-value based on theoretical values. In addition, it investigates the risk for mould growth in different cordwood walls through a sensitivity analysis, determining under which conditions such a construction can be used without the risk for mould growth.

2 BACKGROUND

The origin of the technique is not entirely known, but in Norway, there are documented buildings dating back to the mid-19th century [1]. Cordwood structures were primarily barns and farmhouses built using reused timber during periods of scarce resources and economic hardship [2]. Currently, cordwood masonry is not widely practiced, but it is gaining increasing popularity in certain parts of the world, particularly in North America [3]. In general, the cordwood wall technique can be divided into load-carrying cordwood walls and timber frame infilled with cordwood logs [1]. A few studies have examined the compressive strength of load-carrying cordwood walls [4][5]. However, even fewer studies have researched the thermal performance of cordwood walls, where only theoretical calculations of thermal resistance have been conducted [6][7].

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The insulated cordwood wall of Tradlab TRE consists of a 150 mm cordwood wall, 150 mm exterior wood fibre insulation, a diffusion-open wind barrier, and ventilated wood cladding, avoiding plastic-based products like vapour barriers/retarders or surface treatments. Due to the limited research on this technique, it was essential to investigate its hygrothermal properties.

3 PROJECT DESCRIPTION

Given the limited research on the building physics aspects of cordwood masonry, laboratory experiments measuring heat flux and validated hygrothermal numerical simulations investigating mould growth have been employed. Financed by SirkTRE and Norwegian Museum of Cultural History, and in collaboration with Norwegian Institute of Wood Technology and the Norwegian University of Life Sciences, three different experiments were conducted on the cordwood wall sample in a climate chamber to measure the realistic U-value, both with and without insulation. Hygrothermal simulations were carried out using WUFI® Pro to determine the risk of mould growth in different cordwood wall systems. The experimental data have been used for the validation of the numerical models.

4 METHOLOGY

4.1 PRE-ANALYSIS OF CORDWOOD MASONRY

A pre-analysis was conducted before the main experiment to examine masonry techniques and mortar mixtures. Based on stability, execution, and aesthetics, it was concluded the technique that resembles regular brick head bonding, with each layer offset by half a log width, was the preferred method of masonry. This is also the technique seen in most historical cordwood buildings in Norway. Six different sections were constructed to test various mixtures of clay and aggregate. Three sections used local clay from the Norwegian Museum of Cultural History in Bygdøy, Oslo, while the remaining sections used commercially available clay. The aggregate used was 0/4 mm masonry and plastering sand. The tests concluded that a 1:2 ratio of local clay to aggregate was the preferred mixture for clay mortar, which was then used for the main test wall. The mixing ratio served as a guideline with minor adjustments during masoning based on the mortar's consistency, using 2-3 litres of water per bucket. Each bucket contained 10 litres of clay and 20 litres of aggregate.

With a 1:2 clay to aggregate mortar and reused timber, a cordwood wall sample was constructed within a 1x1 m frame. To limit the extend of cracks and openings in the wall, a slow drying process of the clay was chosen.

4.2 EXPERIMENTAL PROCEDURE

Static and dynamic heat transfer through the cordwood wall element was measured in the laboratory during three different experiments. The chamber was divided into two zones by a thick partition wall with a 1x1 m opening in the middle, where the cordwood wall sample was placed. The assembly of the two walls examined are given in Table 1.

Table 1: Assembly of wall samples examined

Wall system	Cordwood [mm]	Vapour retarder	Insulation [mm][1]	Wind barrier [mm][2]	Timber cladding
CW1	150 mm	-	-	-	-
CW2	150 mm	-	150	25	X

[1]Wood fibre based insulation, $\lambda = 0{,}038$ W/m^{2}K
[2]Wood fibre based wind barrier

Each zone had controllable air temperature (θ) and relative humidity (RH), allowing for the simulation of typical indoor and outdoor climate. The experiments are summarized in Table 2.

Table 2: Summary of the experiments

Experiment	Sample wall	Climate: Exterior zone θ [˚C]	Climate: Exterior zone RH [%]	Climate: Interior zone θ [˚C]	Climate: Interior zone RH [%]	Output
1	CW 1	4	50[1]	23	30	Λ
2	CW 1	4-12	85-70	23	30	U
3	CW 2	4-12	85-70	23	30	U

[1]Measured RH for exterior zone during experiment 1, as the RH was not controlled

In experiment 1, the static heat flux in the logs and clay was measured to calculate the total thermal conductance of CW1 under stable conditions. To obtain static values, the wall was subjected to stable climatic conditions on both the warm and cold sides in the climate chamber. In the interior zone, indoor conditions were simulated with a temperature of 23°C and 30% RH. On the cold side, the temperature was set to 4°C. The humidifier on the cold side was turned off during this experiment. ISO 9869-1:2014 specifies that the minimum duration for testing under stable conditions is 3 days [8]. Therefore, the test was conducted over 4 days without interruptions to ensure stable and accurate results, with the first day allocated for stabilizing the initial conditions to reach equilibrium.

In experiments 2 and 3, the U-value was measured by exposing the test wall to varying climates on the cold side over five days. Due to temperature and moisture dependency of thermal conductivity of materials, fluctuations in heat flow were expected. In the interior zone the climate was stable, with the air temperature set to 23°C and the RH to 30%. In the exterior zone, the air temperature and RH were programmed to simulate typical autumn conditions. Based on weather data from the Norwegian Centre for Climate Services (NCCS), it was decided to vary the climate from 4°C to 12°C and 70% to 85% RH within a 24-hour cycle [9].

4.3 EXPERIMENTAL SETUP

Hukseflux TRSYS-loggers with HFP01 heat flux sensors were used for measuring heat flow in the experiments [10][11]. These logging systems can measure thermal conductivity and thermal resistance through building elements with high accuracy. The systems are primarily used for measuring heat flow in elements according to ISO 9869 [8]. The HFP01 heat flux sensor from Hukseflux measures heat flux [W/m²] through the surface of a sensor. The sensor is sensitive to thermal energy, converting this energy into a voltage corresponding to the heat flux passing through it [11].

On the cordwood wall sample, three general fields for measurement were identified on each side: corner joints and linear joints in the clay, as well as the end grain of the logs. To identify air leaks, thermal bridges, and other irregularities that could affect the results, the wall was thermographed after being subjected to a temperature difference. The surface condition played a significant role in sensor placement. An air gap of 0.1 mm can increase the effective thermal resistance of the sensor by 60%, making it necessary to place sensors on the flattest surfaces possible [11]. Where surface irregularities were too significant, the end grain and clay joints were smoothed by sanding prior to sensor mounting. Despite these efforts, achieving perfectly flat surfaces was not possible. Remaining irregularities and air gaps were filled with thermal paste with a high thermal conductivity of 2.15 W/mK. The width of the joints also influenced sensor placement. The heat flux sensors consist of a circular sensor with a diameter of 32 mm [11]. It was concluded that the measurements were sufficient as long as the inner sensor of 32 mm was within the clay joint. It was still expected this would impact the measured flux in the clay, affecting the final results.

A heat flux sensor was mounted at each of the three fields on both the interior and exterior sides. The measurement points are designated as I1, I2, and I3 for the log, corner joint, and linear joint on the warm interior side, and E1, E2, and E3 for the log, corner joint, and linear joint on the cold exterior side. Each measurement point had two associated thermocouples (temperature sensors) to measure the temperature difference through the section. This comprised a total of 6 heat flux sensors and 12 associated thermocouples i.e. 6 pairs of thermocouples. The heat flux sensors were paired with one sensor on each side of the wall, but not directly opposite each other. This arrangement was chosen to prevent the sensors from interfering with each other's measurements.

Figure 1 shows the setup for experiment 1 from the simulated exterior zone. The thermocouples were mounted with holders featuring a bent profile during to ensure the sensors were pressed against the surface. In experiment 2, the temperature sensors were mounted approximately 1.5 cm away from the wall to include the convective thermal resistance of the air layer near the wall surface.

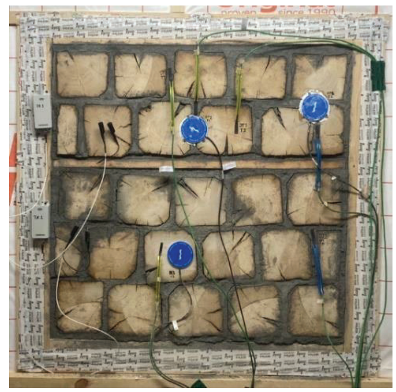

Figure 1: Experimental setup of the CW1 from exterior zone

In experiment 3, the U-value of Test Wall 2 with an exterior insulation layer was measured by exposing the test wall to varying climates on the cold side over five days. The cordwood wall sample was externally insulated with 148 mm thick Hunton Nativo® wood fibre insulation boards, followed by Hunton Vindtett Plus™ 25 mm wind barriers, and an air-ventilated wood cladding.

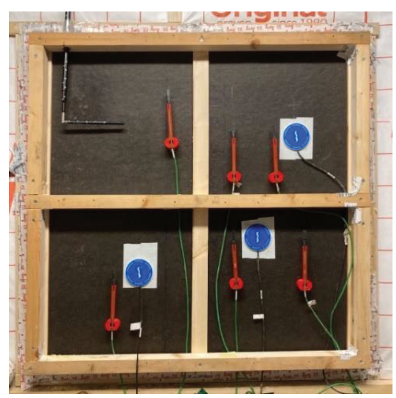

Figure 2: Experimental setup for CW2 from the exterior zone, before cladding was mounted

On the interior side, the heat flux sensors and their corresponding temperature sensors were placed at the same points as in experiments 1 and 2. On the exterior side, the heat flux sensors were placed on the wind barrier panel. The placement on the panel was determined by the positions of the flux sensors on the opposite side. For

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instance, the measurement point alignment was checked to ensure that the paired heat flux sensors were not placed directly opposite each other, as this could affect the measurement results. The heat flux sensors on the cold side were mounted using double-sided tape.

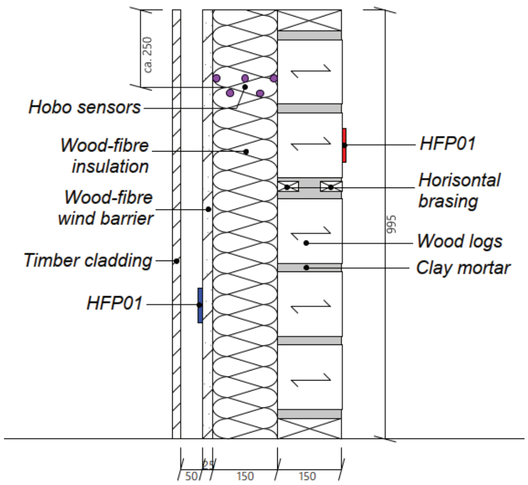

Figure 3: Cross section of sensors on CW2 in experiment 3: HFP01 (red/blue), RH/temp sensors (purple dots in insulation)

Five Hobo Onset RH and temperature sensors, labelled S1 to S5, were evenly distributed through the insulation, as illustrated with purple dots in Figure 3. S1 was closest to the wind barrier, and S5 was closest to the cordwood wall. The data from these sensors were later used to validate the simulations in WUFI® Pro, comparing RH and temperature across the wood fibre insulation.

The fans in the climate chamber created significant air circulation in the room. A plastic screen was mounted in front of the fan to prevent strong airflows from blowing directly onto the wall, which could affect the measurements. However, it was uncertain whether this air circulation could influence the wind speed at the wall surface. As shown in Figure 2, a wind speed sensor was mounted in the upper left corner to measure the air velocity behind the cladding during experiment 3. The sensor measured wind speed in the vertical direction, approximately 1.5 cm from the wall. It could only measure for a period of a few hours at a time, but this was considered sufficient to estimate the wind speed.

4.4 MEASUREMENT OF HEAT FLUX

During the execution of the experiments in the climate chamber, ISO 9869-1:2014 was followed, using the average method as a basis. The average method is based on the principle that thermal conductance Λ and the thermal transmittance U can be calculated by dividing the average measured heat flux by the average temperature difference [8]:

$$\Lambda = \frac{\sum_{j=1}^{n} q_j}{\sum_{j=1}^{n}(T_{sij} - T_{sej})} \tag{1}$$

$$U = \frac{\sum_{j=1}^{n} q_j}{\sum_{j=1}^{n}(T_{ij} - T_{ej})} \tag{2}$$

Λ = thermal conductance [W/m²K]
q_j *= heat flux at index j [W/K]*
T_{sij} *= interior surface temperature at index j [˚C]*
T_{sej} *= exterior surface temperature at index j [˚C]*
U = thermal transmittance coefficient [W/m²K]
T_{ij} *= interior ambient temperature [˚C]*
T_{ej} *= Exterioer ambient temperature [˚C]*

Not all requirements of the standard were met due to the inhomogeneity of the cordwood wall. According to ISO 9869-1:2014, heat flux sensors should be placed so that the measurements represent the entire element [8]. Heat flux sensors and temperature sensors should not be placed near thermal bridges, cracks, or other anomalies that could lead to inaccurate measurements. The sensors should be placed neither near heating nor cooling systems, nor in the airflow from a ventilation system. Heat flux sensors should be mounted directly against the surface to be measured, and if there are any irregularities, a thin layer of thermal paste can be used to fill the air gaps [8].

When measuring thermal conductivity (λ) or conductance (Λ), temperature sensors should be mounted on the surface of the element to be measured. When measuring thermal transmittance (U-value), the temperature sensors should be installed at some distance from the wall to include the convective heat transfer coefficient, or in other words the thermal resistance of interior and exterior surface. The duration of the test should be at least 72 hours if temperatures are stable. When plotting the values from the average method, one will eventually observe that the values converge towards an asymptotic value [8].

4.5 CALCULATION OF U-VALUE

A theoretical heat transfer analysis for the cordwood walls was calculated using the method for upper and lower boundary values for thermal resistance according to ISO 6946:2017 [12]. The thermal resistance (R) for an element is given by the thickness of the material divided by the thermal resistance, or simply the inverse of the thermal conductance:

$$R = \frac{x}{\lambda} = \frac{1}{\Lambda} \tag{3}$$

R = thermal resistance [m²K/W]
x = thickness [m]

For a building component with multiple layers, the total thermal resistance (R_{tot}) must be determined:

$$R_{tot} = R_{si} + R_1 + R_2 + \ldots + R_n + R_{se} \quad (4)$$

R_{tot} = *total thermal resistance [m²K/W]*
$R_1 + R_2 + \ldots + R_n$ = *thermal resistance of the homogeneous layers*
R_{si} = *internal thermal resistance*
R_{se} = *external thermal resistance*

According to ISO 6946:2017, for building components with heterogeneous material layers, an average value of the upper and lower boundary values for the total thermal resistance of the component should be calculated (ISO, 2017):

$$R_{tot} = \frac{R_{upper} + R_{lower}}{2} \quad (5)$$

R_{upper} = *upper thermal resistance [m²K /W]*
R_{lower} = *lower thermal resistance [m²K /W]*

To calculate the upper and lower boundary values, the wall specimen is divided into material layer and sections, shown in Figure 4 [12].

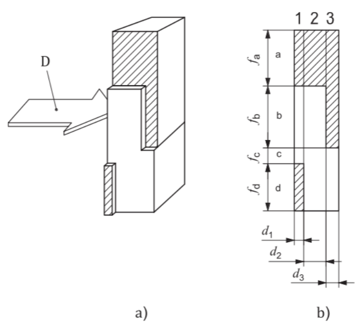

Figure 4: a) Direction of heat flux (D). b) Material layer (1, 2, and 3) and field (a, b, c, and d) [12].

The U-value is then calculated by the inverse of the total thermal resistance of the building element:

$$U = \frac{1}{R_{tot}} \quad (6)$$

The U-value for the cordwood wall was calculated according to the percentage composition of materials in the element. In the calculation of the theoretical U-value of the cordwood wall element, the distribution between logs and clay was 65% and 35%, respectively. The theoretical range of the thermal conductivity for the logs was from 0.29 to 0.37 W/mK, based on studies investigating the thermal conductivity of spruce parallel to the grain [13][14]. The theoretical range of the thermal conductivity for the clay was from 0.48 to 0.96 W/mK based on similar studies on clay mortars [15][16].

For the calculation of the U-value for the experimental elements, the logs still constituted about 65% of the wall. The corner joints were estimated to constitute 14% of the wall, while the linear joints accounted for 21% of the total wall area. This method of area distribution was a simplified approach, assuming each measurement point would have a thermal conductivity representative of the entire element.

4.6 NUMERICAL SIMULATIONS

A sensitivity analysis was conducted on three cordwood walls with different material layers and climate conditions. SCW1 (Simulated Cordwood Wall) represented a traditional cordwood wall with 300 mm thick logs. Two versions of the traditional cordwood wall were modelled, SCW1.a and SCW1.b without and with exterior wood cladding, respectively.

SCW2 represented the TradLab TRE configuration. It consisted of 150 mm cordwood between 48x148 mm studs with a 600 mm centre distance, Hunton Nativo® wood fibre insulation, an exterior wind barrier of Hunton Vindtett Plus™, and ventilated wood cladding. This wall had to versions, as SCW2.a and SCW2.b was modelled without and with a vapour retarder, respectively.

SCW3 included 100 mm cordwood, a vapour retarder, 100 mm continuous insulation, 100 mm wood fibre insulation in a stud frame, a diffusion-open wind barrier, and ventilated wood cladding. This wall was modelled to meet the Norwegian building regulations minimum requirements for U-value [17]. The wall systems are summarized in Table 3 below.

Table 3: Modelled cordwood walls

Wall system	Cordwood [mm]	Vapour retarder[1]	Insulation [mm][2]	Wind barrier [mm][3]	Timber cladding
SCW1.a	300 mm	-	-	-	-
SCW1.b	300 mm	-	-	-	X
SCW2.a	150 mm	-	150	25	X
SCW2.b	150 mm	X	150	25	X
SCW3	100 mm	X	200	25	X

[1]Sd = 10 m
[2]Wood fibre based insultaion, λ = 0,038 W/m²K
[3]Wood fibre based wind barrier

Moisture and mould risk were examined in the three cordwood wall models using WUFI® Pro 1D and the additional program WUFI® Mould Index VTT, based on the Viitaten mathematical mould growth model (or VTT model) [18].

The investigation in the program was conducted as a sensitivity analysis, where certain parameters such as indoor temperature, moisture production and outdoor climate were altered to study how these changes affect the moisture and mould risk in the cordwood wall models. The parameters examined are summarized in Table 4.

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Table 4: Parameters of the sensitivity analysis

Parameter	SCW1.a	SCW2.a	SCW3
Location	Oslo, Røros, Bergen	Oslo, Røros, Bergen	Oslo, Røros, Bergen
RH at start	70%	60%, 70%, 80%	70%
Interior temp.	15˚C	15˚C, 20˚C	20˚C
Internal humidity class	1	1, 2	4, 5
Alteration	Exterior cladding (SCW1.b)	Vapour retarder (SCW2.b)	-

In the simulations in WUFI® Pro, average outdoor climates from three Norwegian cities were used to represent warm-temperate, cold-temperate, and polar climate according to Köppen's climate zones: Bergen, Oslo, and Røros.

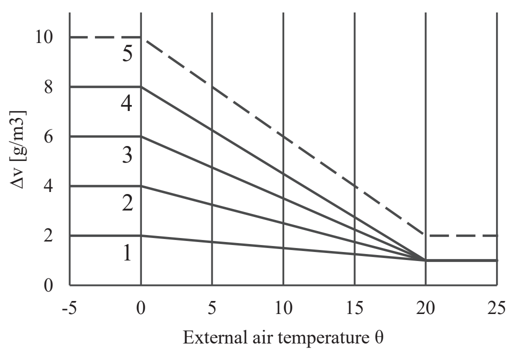

Figure 5: Internal humidity classes 1 to 5 according to NS-EN ISO 13788:2012

The indoor climate used for the simulations is built into WUFI® Pro and is based on the internal humidity classes from the standard NS-EN ISO 13788:2012. Appendix A of the standard describes five categories for indoor moisture load in buildings in a maritime climate, as shown in Figure 5 [19]. All simulations were conducted over a 3-year period, starting from July 1, and each wall façade directed towards the most challenging orientation, assumed to be the one with the most driving rain and least sun exposure.

4.7 MOISTURE AND MOULD GROWTH ANALYSIS

For analysing moisture conditions and mould growth index in the simulations, the additional program WUFI® Mould Index VTT was used. The model calculates an index for mould growth conditions on wood surfaces based on the duration of favourable conditions concerning temperature, relative humidity, and nutrients [20]. The model presents mould growth with an index on a scale from 0 to 6, where the scale is classified based on visual findings in a laboratory setting [18]. For interior surfaces, there is zero tolerance for a mould growth index above 1 due to indoor health concerns related to indoor air pollution. Further out in the construction, which is enclosed, mould growth up to an index of 2 is accepted. The general assessment is summarized in Table 5.

Table 5: Assessment of mould growth on building surfaces

General assessment	Mould Growth Index (MGI)	
	Interior surface	Exterior surface
Usually acceptable	< 1	< 2
Additional criteria or investigations are needed for assessing acceptability	1-2	2-3
Usually not acceptable	> 2	> 3

WUFI® Mould Index VTT classifies materials into sensitivity classes. *Untreated wood*, which is defined as very sensitive, was chosen for the wood fibre insulation. *Paper coated products/wood-based boards*, which are defined as *sensitive*, was chosen for the wood fibre wind barrier.

5 RESULTS

5.1 MEASURED CONDUCTANCE AND U-VALUE

Figure 6 to Figure 8 visualise the development of heat transfer in the cordwood wall during experiment 1-3, presented according to the average method.

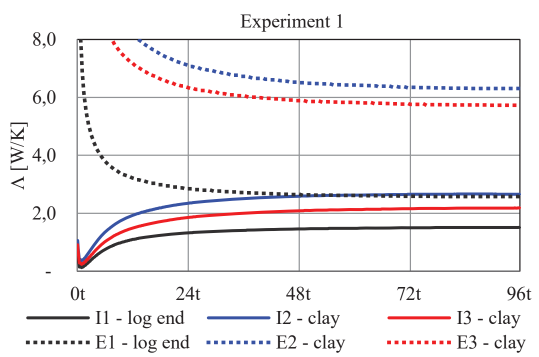

Figure 6: Results from experiment 1 on CW1 presented through the average method

For CW1 in experiment 1, the measured thermal conductance in the log end, parallel to the grain was relatively stable, with a lower limit of 1.51 W/K at I1 and an upper limit of 2.57 W/K at E1. The range was greatest for the clay, with the biggest difference at 3.6 W/K between the internal and external corner joints with I2 at 2.7 W/K and E2 at 6.3W/K.

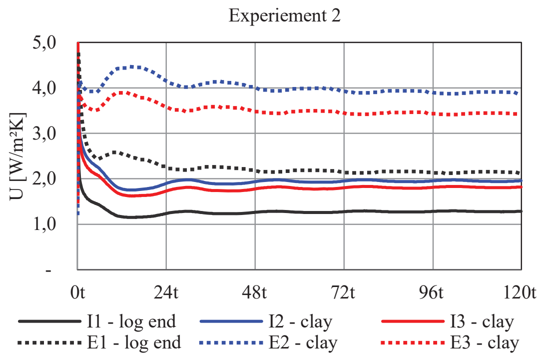

Figure 7: Results from experiment 2 on CW1 presented through the average method.

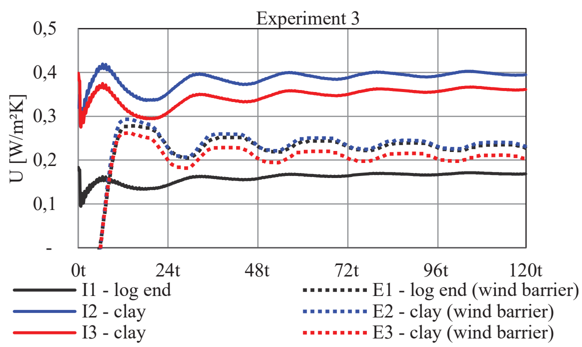

Figure 8: Results from experiment 3 on CW2 presented through the average method

The subsequent experiments, 2 and 3, followed the same pattern, where the wooden logs mostly measured the lowest U-values of their respective sides (except for E1 in experiment 3). Furthermore, the clay corner joints I2 and E2 measured the highest U-values in all experiments, while the linear joints I3 and E3 measuring slightly lower values than the corner joints. Additionally, the measurements from the interior zone during experiment 3, I1-I3, were significantly unstable compared to the exterior measurements during the same experiment.

The differences and variations observed in the measurements means the results should be considered with uncertainty. However, by calculating the mean between the internal and external measurements, the results are within the expected ranges of their respective materials, shown Table 6.

Table 6: Results from experiment 1, 2, and 3

Field	Experiment			
	1		2	3
	$\bar{\Lambda}$ [W/m²K]	$\bar{\lambda}$ [W/mK]	$\bar{U}$ [W/m²K]	
1: Log end	2,04	0,32	1,73	0,20
2: Corner joint	4,48	0,69	2,97	0,31
3: Linear joint	3,96	0,61	2,64	0,28

The mean thermal conductance $\bar{\Lambda}$ of for the log parallel to the grain was 2.04 W/m²K, resulting in a mean thermal conductivity $\bar{\lambda}$ at 0.32 W/mK for an element with a thickness of 155 mm, which was the average thickness of the logs in the cordwood wall sample. With the same thickness for the clay in the cordwood wall sample the thermal conductivity ranges from 0.61 to 0.69 W/mK.

Table 7: Calculated U-value of the cordwood wall samples

Calculation	U-value [W/m²K]	
	CW1	CW2
Theoretical range	1.51 - 2.23	0.190 – 0.198
Static experiment	1.89	-
Dynamic experiment	1.96	0.223

Table 7 shows the calculated U-value for CW1 at 1.89 W/m²K based on experiment 1 and 1.96 W/m²K in experiment 2, respectively, which is within the range based on theoretical calculations i.e., 1.51 to 2.23 W/m²K. The insulated wall CW2 had a measured U-value of 0.223 W/m²K. This was higher than the expected theoretical range of 0.190 to 0.198 W/m²K, most likely because of unstable measurements during experiment 3.

5.2 VALIDATION OF MODEL

The simulation model was verified by simulating the measured climatic conditions from experiment 3 in WUFI® Pro and comparing the measured and simulated RH and temperature in the wood fibre insulation. The data from the measured internal and external RH and temperature during experiment 3 were processed and converted into a climate file adapted to WUFI® Pro's specifications. The data were converted to average hourly measurements, as WUFI calculates on an hourly basis. The exterior conditions during experiment 3 is shown in Figure 9.

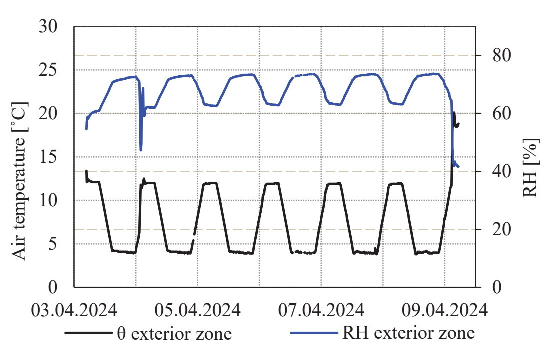

Figure 9: Exterior conditions during experiment 3

Figure 10 shows the results from the verification of the simulation model in WUFI at measurement point S1, located furthest out in the wood fibre insulation.

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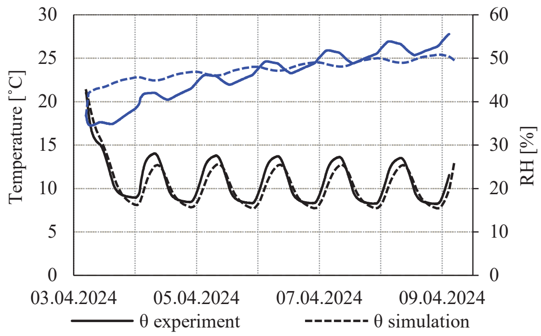

Figure 10: Comparison between measured and simulated RH and temperature θ at S1

The verification displays good agreement between the simulated and the measured temperature. The simulated temperature was generally slightly lower than the measured temperature, but both temperatures fluctuated between approximately 8˚C to 14˚C, in sync with the temperature change in the external zone.

The simulated RH deviated from the measured RH at point S1. Both started at around 37% RH, but the simulated RH increased rapidly within the first hour before stagnating, in contrast to the measured RH. Additionally, the results show that the simulated and measured RH had opposite cycles, and the fluctuations in the measured RH were more pronounced. These differences show that the input values for the wood fibre insulation were inadequate. Unfortunately, the manufacturer did not have more detailed documentation of the product. The validation at points S2, S3, S4, and S5 followed a very similar trend as in S1.

5.3 SIMULATED MOULD GROWTH

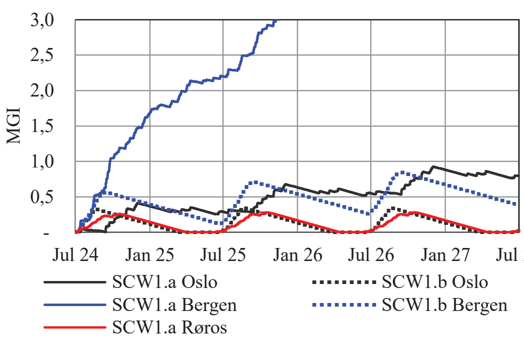

Figure 11: MGI levels of SCW1.a and SCW1.b with 15 °C indoor temperature and internal humidity class 1

In Figure 11, the MGI (mould growth index) is presented for SCW1.a and SCW1.b simulated in the climates of Oslo, Bergen and Røros, with an indoor climate of 15 °C and internal humidity class 1. SCW1.a in Oslo shows a slight development, obtaining a MGI of 1 after three years, which is within the acceptable levels of mould growth for outside surfaces. However, the MGI showed no sign of stabilizing, and could possibly reach unacceptable levels without maintenance of the wall. With exterior cladding, SCW1.b in Oslo was no longer susceptible to mould on the exterior surface, however, the MGI on the interior surface reaches 0.4.

Within 18 months, the MGI on the exterior surface of SCW1.a in Bergen goes beyond 3. With exterior cladding, the MGI on the exterior surface of SCW1.b in Bergen is zero, but instead the mould growth on the interior surface is increasing, presumably exceeding 1 after more than 3 years. SWC1.a in a polar climate like Røros indicates low MGI on the exterior surface.

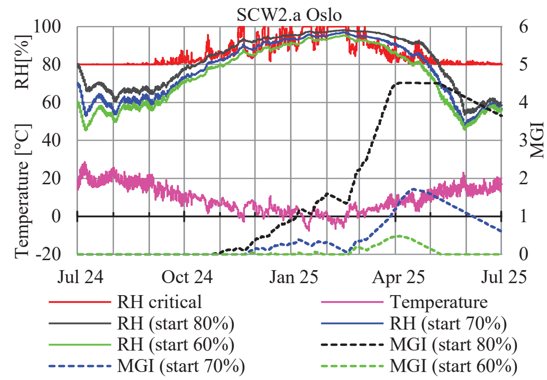

Figure 12: RH, temperature and MGI for SCW2.a in Oslo presented through a Folos mould growth diagram

Figure 12 shows the Folos mould growth diagram for SCW2.a in Oslo, with internal humidity class 1 and variating building moisture at the start of the simulation. With 80% RH at the start (black), the RH remained above the critical RH from autumn throughout winter and spring reaching up to 4.5 on the internal surface.

With 70% RH at the start (blue), the RH stayed above the critical RH for much of autumn and winter as well, but with less development rate compared to 80% RH at start, reaching only 1.7 during the spring. By late March, the MGI decreased significantly without further signs of development. With 60% RH at the start (green) the MGI reached its peak at 0.5 in the spring and decreased back to 0 within a few weeks. Mould growth was at its highest for SCW2.a during the first year, and the MGI had a decreasing trend after three years for the simulations in Oslo, Røros, and Bergen, shown in Figure 13.

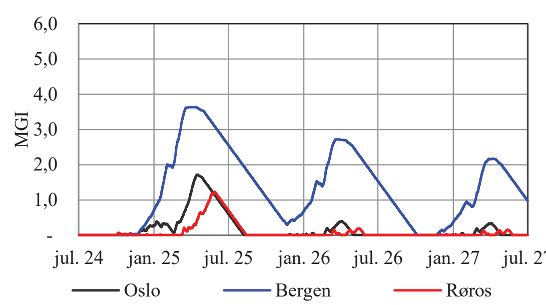

Figure 13: MGI for SCW2.a over 3 years

Further simulations indicate that with an indoor temperature of 20°C, SCW2.a has acceptable MGI levels for both internal humidity class 1 and 2, given the construction humidity is 60% or below from the start. The simulation of SCW2.b with 15°C internal temperature indicate that the addition of a vapour retarder will not necessarily improve its resistance to mould, as the MGI is rising towards an unacceptable level on the interior surface. SCW3, when simulated in the Bergen climate with internal humidity class 4 and indoor temperature of 20°C had no development of MGI. With internal humidity class 5, SCW3 had periods during the summer where the MGI on the interior surface increased. After 3 years, the highest MGI for this simulation was 0.7, and it had a rising trend.

6 CONCLUSIONS

This study provides an introductory assessment of the building physical aspects of cordwood walls. The results must be interpreted with caution due to uncertainties, simplifications in the experiments and simulations, and potential variations in design and material use.

The results from the laboratory experiments on a 150 mm thick cordwood wall made of spruce and clay mortar measured a U-value of 1.89 W/m²K based on measured thermal conductivity and 1.96 W/m²K based on directly measured U-value, within the expected range of 1.51 to 2.23 W/m²K. The same cordwood wall, when combined with 150 mm exterior wood fibre insulation, a wood fibre-based wind barrier with high permeability, and ventilated wooden cladding, measured a U-value of 0.223 W/m²K, higher than the theoretical range of 0.190 to 0.198 W/m²K. The calculated thermal conductivity of the spruce parallel to the grain and the clay mortar was reasonable compared to other studies.

However, the measurements only provide an indication of the wall system's thermal properties. Air gaps between the insulation and the cordwood wall have likely increased the measured U-value. Measuring a cordwood wall, which is inherently inhomogeneous, is challenging due to uneven surfaces and air leaks in continuous cracks. These leaks are hard to quantify, providing many potential sources of error. Despite the lack of a standardized method for measuring the U-value of inhomogeneous elements with heat flux sensors, the experiments are considered successful, though the sources of error weaken the reliability of the results.

The validation of the simulation model showed good agreement between measured and simulated temperature in SCW2. The respective agreement was weaker for the RH, mostly because of missing accurate input for hygroscopic properties of the insulation. This affects the interpretation of the numerical simulations, suggesting that, in reality, one could expect slightly higher moisture levels within the wall, thereby increasing its vulnerability to mould growth.

The simulations indicate that the most significant parameter for avoiding mould growth were low initial building humidity. A traditional cordwood wall, simulated with SWC1, showed mostly its ability to eradicate mould growth when having the opportunity to dry out. This is in line with the end grain's ability to dissipate moisture effectively. SCW2, an externally insulated cordwood wall without a vapour retarder, had low moisture resistance and less capacity for drying out at low temperatures. However, the simulations indicate the mould growth is sufficiently low if the construction had a low initial RH level and low moisture excess. SCW3, an externally wood fibre insulated cordwood with a vapour retarder, showed few problems in the simulations regarding moisture and mould growth. With the highest moisture class, increasing mould growth was found on the interior surface, according to the simulation. This can be prevented by either decreasing the indoor moisture excess Δv e.g. by reducing the generation of moisture indoors or increasing the air exchange with the outdoors, or by increasing the interior surface temperature (and the air temperature indoors).

The potential applications for a traditional cordwood wall are primarily buildings with no requirements to energy efficiency as it insulates poorly, and where moisture exposure is low. This could include simple cabins, sheds, or constructions for simple usage. The many air leakages in a cordwood wall are problematic and are a concern that should be addressed in further studies. The thickness of the wall sample used in this study is less than most traditional cordwood walls, as they usually are closer to 30-40 cm, and air leakages may be easier to handle for thicker walls.

The potential applications for an externally insulated cordwood wall without a vapour retarder, like CW2 and SCW2, could be in residential buildings, offices, and other structures with an internal moisture load equivalent to internal humidity class 2, provided normal indoor temperatures and an adequately dry local climate. However, further investigations are necessary to determine if such a wall meets the minimum energy requirement. The calculated U-value of 0.22 W/m²K precisely meets the minimum requirement set by Norwegian building regulations. Therefore, it is not suitable as a climate barrier for buildings aiming to be energy efficient. The regulations also require the use of a vapour barrier in exterior structures, which this wall lacks. The simulations in this study indicate that mould growth does not occur above acceptable levels if the

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structure is kept adequately warm and dry. At lower indoor temperatures, this wall could potentially also be used in areas with low moisture loads, such as cabins and vacation homes in regions similar to the climates of Oslo or Røros.

An insulated cordwood wall with a vapour retarder, like SCW3, can potentially be used in most buildings concerning energy efficiency and moisture protection. However, this assumes that issues like dust and debris are managed regarding maintenance and cleaning. This wall system may be applicable for moisture buffering in bathrooms and could presumably facilitate good interior acoustics with its uneven and profiled surface.

Further research of the heat loss and mould risk in cordwood walls is recommended, as well as exploring ways of improving the masonry technique, its hygrothermal impact on indoor environment, and its environmental footprint.

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