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Hygrothermal performance of wood-hemp insulation in timber frame wall panels with and without a vapour barrier

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Abstract

An in situ experiment on a full-scale timber frame test building was carried out to study the hygrothermal performance of wood-hemp composite insulation in timber frame wall panels with and without a vapour barrier. The heat transfer properties and the likelihood of mould growth and condensation in the panels were compared. Step changes in the internal relative humidity were performed to explore the effects of high, normal and low internal moisture loads on the wall panels. No significant difference in the average equivalent thermal transmittance (U-values) between the panels with and without a vapour barrier was observed. The average equivalent U-values of the panels were close to the U-values calculated from the manufacturers' declared thermal conductivity values of the insulation. The likelihood of condensation was higher at the interface of the wood-hemp insulation and the oriented strand board (OSB) in the panel without a vapour barrier. In terms of the parametric assessment of the mould germination potential, the relative humidity, the temperature and the exposure conditions in the insulation-OSB interfaces of the panel without a vapour barrier were found to be more favourable to the germination of mould spores. Nonetheless, when the insulations were dismantled, no mould was visually detected.

Key words: Bio-based insulation material; wood-hemp insulation; U-value; mould spore germination; vapour barrier.

1. Introduction

Domestic and non-domestic buildings are major contributors to carbon emissions in the UK [1]. In the domestic sector, the highest portion of energy is spent on maintaining indoor thermal comfort through space heating [1]. The energy demand for space heating can largely be reduced by adequately insulating poorly insulated and uninsulated buildings and maintaining improved insulation standards for new

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buildings [2]. However, the most commonly used thermal insulation materials are produced either from minerals or from petro-chemical-based raw materials [3]. The extraction of these raw materials causes resource depletion, and the manufacturing process demands intensive energy use.

Due to the growing importance of sustainable materials in the construction industry, new materials and technological solutions are widely sought out [4]. Sustainable construction requires a focus on using renewable and low-embodied energy building materials along with reducing the building's operational energy demand. In terms of the hygrothermal performance of building fabric, a trend is emerging in the green building industry to explore the possibilities of widespread use of "breathing" walls or "vapour open" walls, which are walls without vapour barriers that hygrothemally interact with the boundary conditions. Results from full scale test buildings show that the moisture content inside a vapour open wall is better managed [5, 6], while the use of a vapour barrier can result in high interior relative humidity, large oscillations in the interior relative humidity and excessive moisture load on the construction [6]. Lstiburek [7] observed that vapour barriers, as opposed to materials with controlled vapour permeability, were unnecessary for most of the climatic conditions including the warm-humid one. Lstiburek [7] further noted that vapour barriers, while designed to prevent assemblies from getting wet, might prevent assemblies from getting dried. Furthermore, the hygroscopic buffering capacity of the insulation materials can be utilised in a vapour open wall [6].

As opposed to conventional thermal insulations, bio-based insulations are manufactured from renewable materials and carry very low embodied energy. A recent case study on a hypothetical building model in Finland [8] shows that the life cycle energy balance of cellulose fibre insulation is the lowest among all of the building materials including EPS (expanded polystyrene) and glass wool insulations. Among the bio-based insulations, composite hemp insulations are produced fully or partially from hemp fibres. Hemp is considered to be an environmentally friendly and high-yield crop, ideal for a crop rotation-based sustainable agricultural system [9]. In terms of global warming potential, hemp fibre is a carbon-negative material. Compared to stone wool, hemp insulation is considered a highly sustainable material [4]. Furthermore, due to its excellent hygrothermal and acoustic properties, hemp insulation is regarded as a highly suitable material for building applications [4].

However, limited information is available on the hygrothermal performance of hemp and composite hemp insulations in relation to their performance in a vapour open wall construction compared to that in a conventional wall construction with a vapour barrier. In terms of in situ monitoring, Rasmussen and Nicolajsen [10] studied the hygrothermal performance of flax, cellulose and mineral wool insulations in the walls and lofts of a number of houses. The insulations were placed between 100 mm thick lightweight internal concrete blocks and 9 mm thick external gypsum plasterboards protected by a rain screen. The monitoring was carried out within a relative humidity range of 20% to 60%. Rasmussen and Nicolajsen did not find any evidence of critical moisture content in the insulation that can cause biodegradation. In a separate in situ study, Nicolajsen [11] compared stone wool and cellulose insulations installed in a north-facing timber frame wall with a steady interior temperature of 20°C and relative humidity of 60%. The thermal transmittance values of both insulations were close to the thermal transmittance values calculated from the manufacturers' declared thermal conductivity values. In terms of moisture content within the insulation, there was no risk of biodegradation. Latif et al. [12] compared the hygrothermal performance of hemp and stone wool insulations in vapour open timber frame wall panels in service conditions, incorporating moderate and high interior relative humidity. While no significant difference was observed in the average thermal transmittance of the wall panels with hemp and stone wool insulations, the likelihood of condensation was higher in the panel containing stone wool insulation. Labat et al. [13] compared 6 different wall assemblies with mineral wool, wood fibre and cellulose insulations in a full scale timber frame building to validate a numerical model. They observed that the U-values of the wood fibre and cellulose insulations decreased by 53% and 46% from their dry value as a result of exposure to high internal relative humidity.

In terms of the steady-state hygric and thermal properties of composite hemp insulations, Latif et al. [14] characterised the hygric properties of five commercially available composite hemp insulations in the UK. Collet et al. [15] determined the moisture adsorption and vapour transfer properties of two hemp-wool insulations. Korjenic et al. [16] experimentally determined the moisture dependent thermal conductivity of hemp insulation in a steady state thermal gradient. This method of measuring the thermal conductivity of moistened insulation is contentious due to the potential moisture movement along the depth of the insulation while attaining a steady state. In general, the steady state hygric and thermal properties of composite hemp insulations are useful as material input data in numerical hydrothermal simulation tools.

Bio-based materials are often perceived as prone to mould growth. For hemp fibres, Nykter [17] observed the presence of microbes in the bast fibres of hemp insulations from the beginning of the fibre processing. Nykter further noted that microbial emission was the highest at 90% relative humidity, while Rao et al. [18] observed that increasing mould spore transportation from the building envelope to the building interior at the wetting period of 6 weeks at 90% relative humidity was not statistically significant. Johansson et al.[19] observed that, for wood based building materials exposed to fluctuating relative humidity of 60% and 90%, mould growth depended more on the duration of favourable and unfavourable conditions than on the accumulated period of favourable conditions.

There is a clear gap in knowledge in terms of understanding the comparative hygrothermal performance of wood-hemp wall panels, with and without a vapour barrier, in internal relative humidity conditions ranging from low to high values. In this paper, the thermal transmittance, relative humidity, moisture conditions and mould growth potential of a wood-hemp composite insulation are determined in timber frame wall panels, with and without a vapour barrier, using interior boundary conditions incorporating very high relative humidity (90%), moderate relative humidity (50%-60%) and low relative humidity (less than 40%). These particular interior relative humidity boundary conditions were selected because they are commonly encountered in buildings in the UK.

The present paper is a follow-up to the work reported by Latif et al. [12], which compared the hygrothermal performance of two timber frame wall panels containing hemp and stone-wool insulations. This paper focuses on the hygrothermal performance of timber frame wall panels, with and without a vapour barrier, with emphasis on wood-hemp composite insulation only. The work presented in this paper uses a similar methodology to that used by Latif et al. [12], with appropriate amendments, as presented in sections 2 and 3 of this paper.

2. Theory

This section briefly describes the methods of determining the thermal transmittance and assessing the likelihood of mould spore germination.

2.1 Thermal Properties

2.1.1 Methods for numerical determination of U-value:

The U-value (thermal transmittance) is the inverse of the R-value (thermal resistance). The calculations of the U-value of wall panels are based on BS EN ISO 6946:2007 [20]. The methods are detailed below.

2.1.1.1 Calculation of the U-value of wall panels consisting of homogeneous layers:

The total thermal resistance, R_T, of a plane building component consisting of thermally homogeneous layers perpendicular to the heat flow is given by the following expression:

$$R_T = R_{si} + R_1 + R_2 + \ldots + R_n + R_{se} \qquad [1]$$

where

R_{si} is the internal surface thermal resistance,

$R_1, R_2 \ldots R_n$ are the design thermal resistances of each layer, and

R_{se} is the external surface thermal resistance.

2.1.1.2 Calculation of the U-value of wall panels consisting of homogeneous and heterogeneous layers:

The total thermal resistance, R_T, of a building component consisting of homogeneous and heterogeneous layers parallel to the surface is calculated as the arithmetic mean of the upper and lower limits of the resistance:

$$R_T = (R'_T + R''_T)/2 \qquad [2]$$

where

R'$_T$ is the upper limit of the total thermal resistance and R"$_T$ is the lower limit of the total thermal resistance. The upper limit of resistance, R'$_T$, is determined by assuming one-dimensional heat flow perpendicular to the surface of the component. This is given by the following expression:

$$1/ R'_T = f_a/ R_{Ta} + f_b/ R_{Tb} +\ldots+ f_q/ R_{Tq} \qquad [3]$$

where

$R_{Ta}, R_{Tb}\ldots R_{Tq}$ are the thermal resistances from environment to environment for each section, calculated using Equation [1], and

$f_a, f_b\ldots f_q$ are the fractional areas of each section.

Fig. 1 shows the horizontal cross section of a notional wall panel, where a, b and c are the widths of each perpendicular section and d1, d2 and d3 are the thicknesses of layer 1, layer 2 and layer 3, respectively.

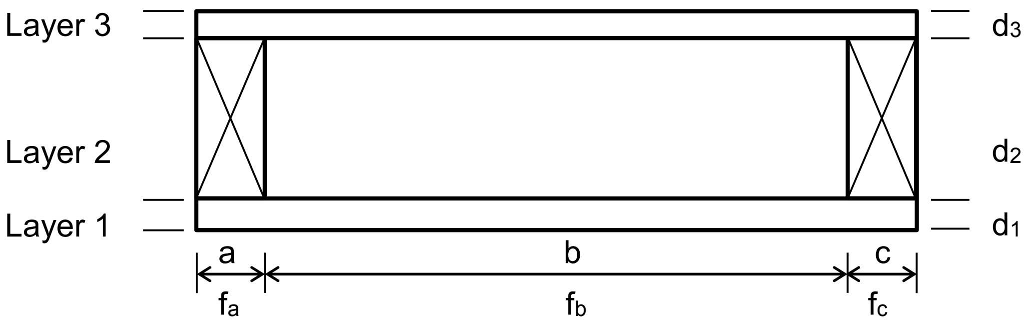

Fig. 1. Horizontal cross section of a notional wall panel.

The lower limit of the total thermal resistance, R"$_T$, is determined by assuming that all planes parallel to the surfaces of the components are isothermal surfaces. The equivalent thermal resistance, R_j, for each thermally heterogeneous layer is calculated using the following equation:

$$1/ R_j = f_a/ R_{aj} + f_b/ R_{bj} +\ldots+ f_q/ R_{qj} \qquad [4]$$

where

R_{aj}, R_{bj}…….. R_{qj} are the thermal resistances of the fractional areas f_a, f_b… f_q of layer j.

The lower limit of the thermal resistance is determined by using Equation [1]:

$$R''_T = R_{si} + R_1 + R_2 + \ldots + R_n + R_{se} \quad [5]$$

2.1.1.3 Estimation of error:

The maximum relative error in the thermal transmittance or U-value, e, calculated as a percentage, is:

$$e = ((R'_T - R''_T)*100)/\ (2\ R_T) \quad [6]$$

2.1.2 In situ determination of U-value

ISO 9869 [21] describes the method for in situ measurement of the U-value of building elements. The U-value is obtained by dividing the mean density of heat flow rate by the mean internal and external temperature difference, when the average U-value is taken over a long period of time, i.e., more than 72 hours of data for a heavy weight structure and at least three nights of data for a lightweight structure. The U-value is determined from the following equation:

$$U = \frac{\sum_{j=1}^{n} q_j}{\sum_{j=1}^{n} (T_{ij} - T_{ej})} \quad [7]$$

where

U is the thermal transmittance (W/m^{2}K), q is the density of the heat flow rate (W/m^2), T_i is the interior ambient temperature (°C), and T_e is the exterior ambient temperature (°C). In this paper, the term “equivalent U-value” is used instead of “U-value” in relation to the in situ measurements to account for the added effect of relative humidity, enthalpy flow and phase change on the heat flux through the building envelope.

2.2 Mould spore germination

The likelihood of germination and growth of mould on a surface depends on the combination of temperature, moisture, substrate type, exposure time and the type of mould species [22]. The relationship between these parameters in relation to the risk of mould spore germination is often expressed by isopleth curves [23]. Fig. 2 shows the germination isopleths, developed by Sedlbauer, incorporating the lowest isopleth for mould for substrate class 1, or biodegradable substrates (LIM I). The lowest isopleth for mould (LIM) curves are developed by analysing the combined growth conditions of all fungal species, which represents the worst-case scenario for mould spore germination.

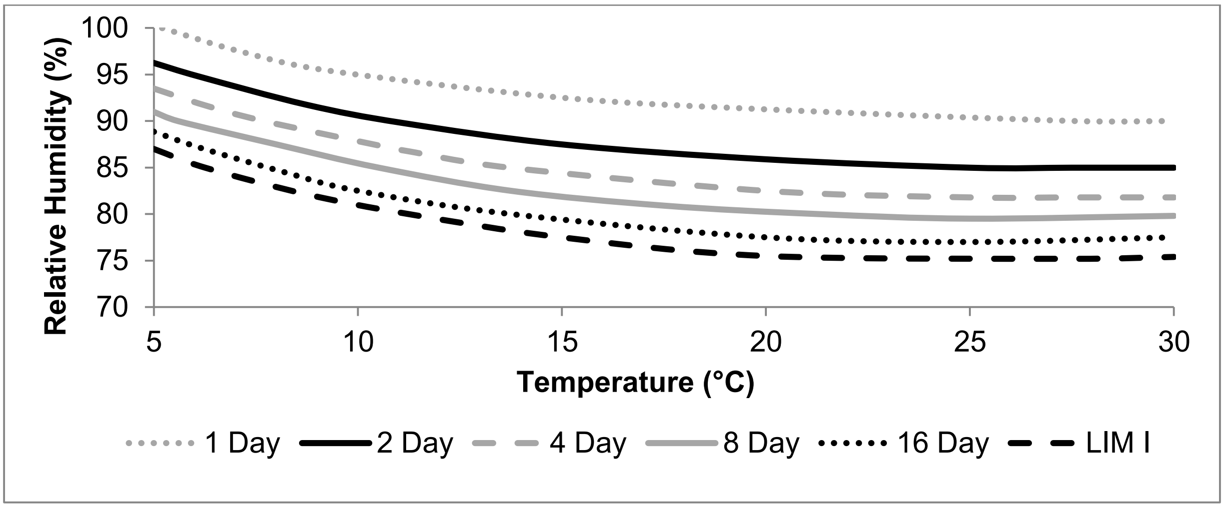

Fig. 2. Sedlbauer's isopleth system for substrate class 1 [23].

3. Material and methods

3.1 The test material

The wood-hemp composite insulation selected in this study contains 30% hemp fibres, 60% wood fibres and 10% polyester. The insulation has a density of 55 Kg/m^3 and the manufacturer's declared thermal conductivity at dry condition is 0.038 W/mK.

Before installation, the insulation samples for both panels were conditioned at 23 (±2)°C temperature [24] and 50% relative humidity [25] to simulate the level of hygrothermal exposure assumed to be encountered by insulations in spaces where construction materials are stored. Based on the adsorption-desorption isotherms of wood-hemp insulation [14], the average adsorbed water content in composite hemp insulation for this exposure is calculated as 3.59 Kg/m^3 and the range between adsorption and desorption is calculated as 3.33 Kg/m^3 to 3.85Kg/m^3.

3.2 The test panels and sensors

3.2.1 The test panels

The 600 mm X 1800 mm test panels (Panel A and Panel B) consist of a number of layers, as shown in Fig. 3.

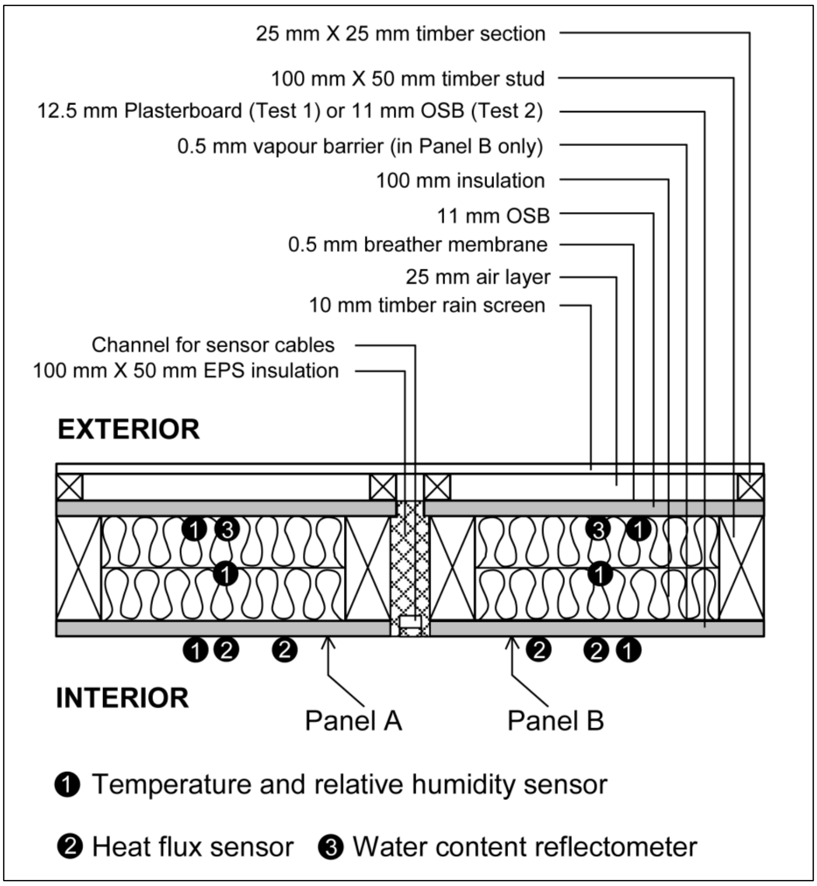

Fig. 3. Horizontal cross section showing Panel A, Panel B and the sensor locations.

From inside to outside, these layers are 12.5 mm plasterboard (PB) used in Test 1 or 11 mm oriented strand board (OSB) used in Test 2, vapour barrier (in Panel B only), 100 mm insulation, 11 mm OSB, 0.5 mm breather membrane, 25 mm air gap, and 10 mm X 100 mm timber rain screen with 30 mm overlaps. During both tests, Panel A is open to vapour and Panel B includes a vapour barrier. The wall Panel A and the wall Panel B were installed on the eastern wall of the test building. The test building is described in section 3.3.

3.2.2 Sensors

Temperature and relative humidity sensors

CS215 temperature and relative humidity sensors from Campbell Scientific were used to measure the temperature and relative humidity together as shown in Fig. 3. The accuracy of the relative humidity measurement at 25 °C is ±4% over 0%-100% relative humidity, while the accuracy of temperature measurement is ± 0.9 °C over -40 °C to +70 °C. The length of the sensor is 180 mm and the average diameter is 15 mm.

Heat flux sensors

HFP01 heat flux sensors by Hukseflux were used to measure the heat flux through the wall panels, as shown in Fig. 3. The measurement range is between -2000 W/m^2 and +2000 W/m^2 and the accuracy is ± 5% on the walls. The thickness of the sensor is 5 mm and the diameter is 80 mm. Because the diameter of the heat flux sensor is small compared to the dimension of the wall panels, the overall effect of the placement of the heat flux sensor on moisture flow can be assumed to be negligible.

Water content reflectometers

The CS616 water content reflectometer uses time-domain measurement methods to determine the volumetric water content (VWC) of porous media. The probe consists of two stainless steel rods that can be inserted from the surface. The length of each rod is 300 mm, the diameter is 3.2 mm and the spacing between the rods is 32 mm. The accuracy is ± 2.5% VWC in the measurement range of 0% to 50% VWC and the precision is 0.05% VWC.

3.3 The test building

The timber frame test building (Fig. 4) was constructed near the Centre for Alternative Technology in Wales, UK. The timber frame test building was 3 metres long and 2.4 metres wide (Fig. 5). The height of the test building was 2 metres along the eaves and 2.4 metres along the ridge. The test building incorporated the two test wall panels in the eastern wall to accommodate the insulation samples. Except for the test wall panels, all of the other walls, floor and roof of the test building were insulated with 100 mm expanded polystyrene (EPS) insulation (Fig. 6), providing an approximate wall U-value of 0.3 W/m^2K.

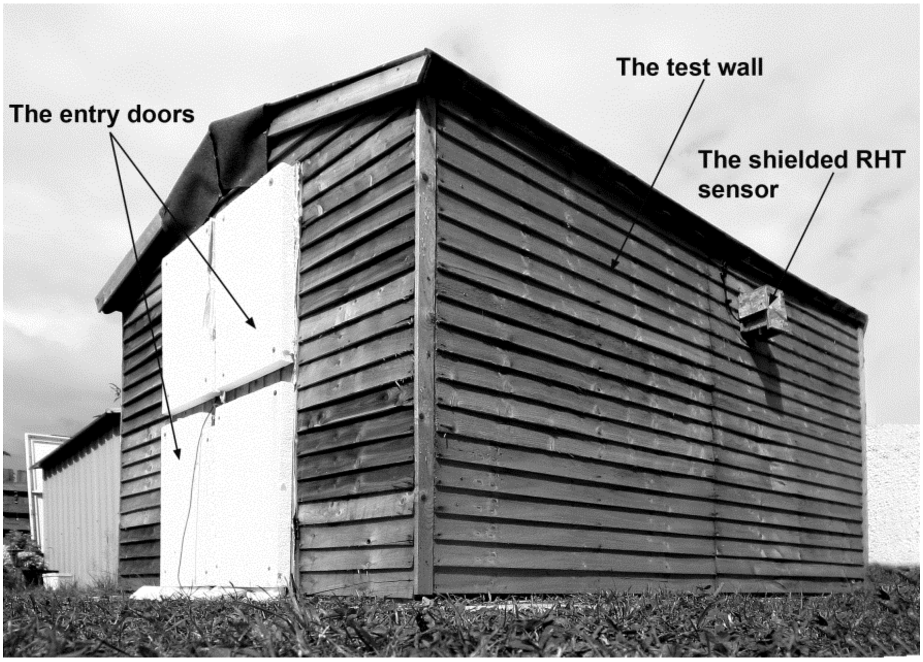

Fig. 4. The test building showing the position of the test wall, the entry doors and the temperature and relative humidity (RHT) sensor.

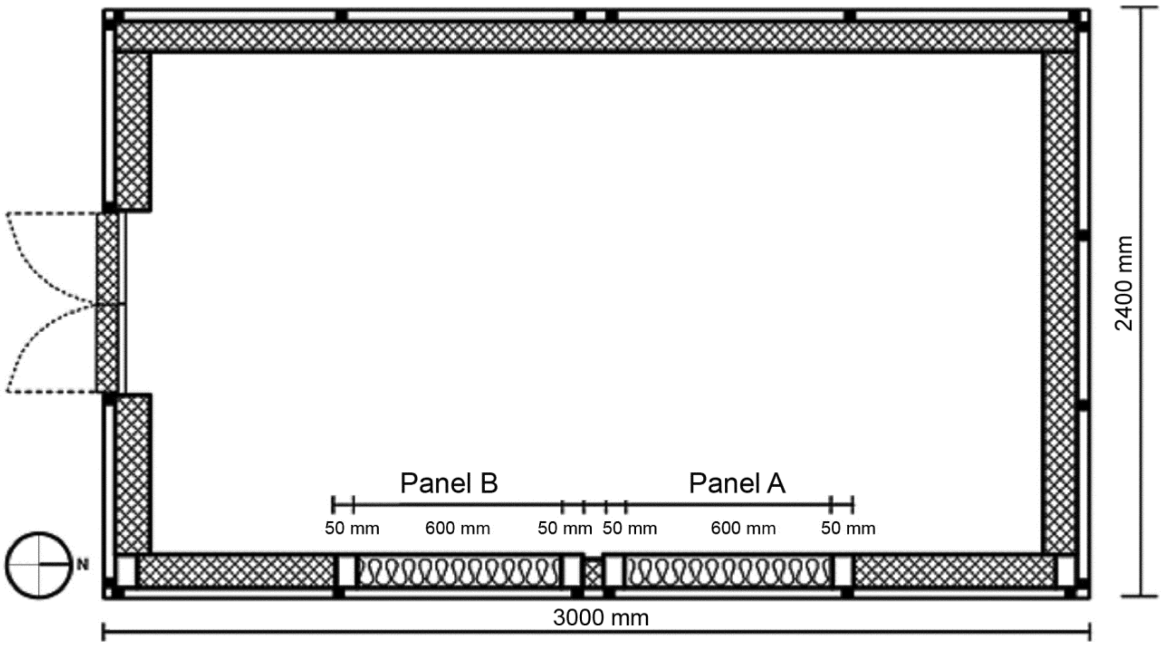

Fig. 5. Plan of the test building.

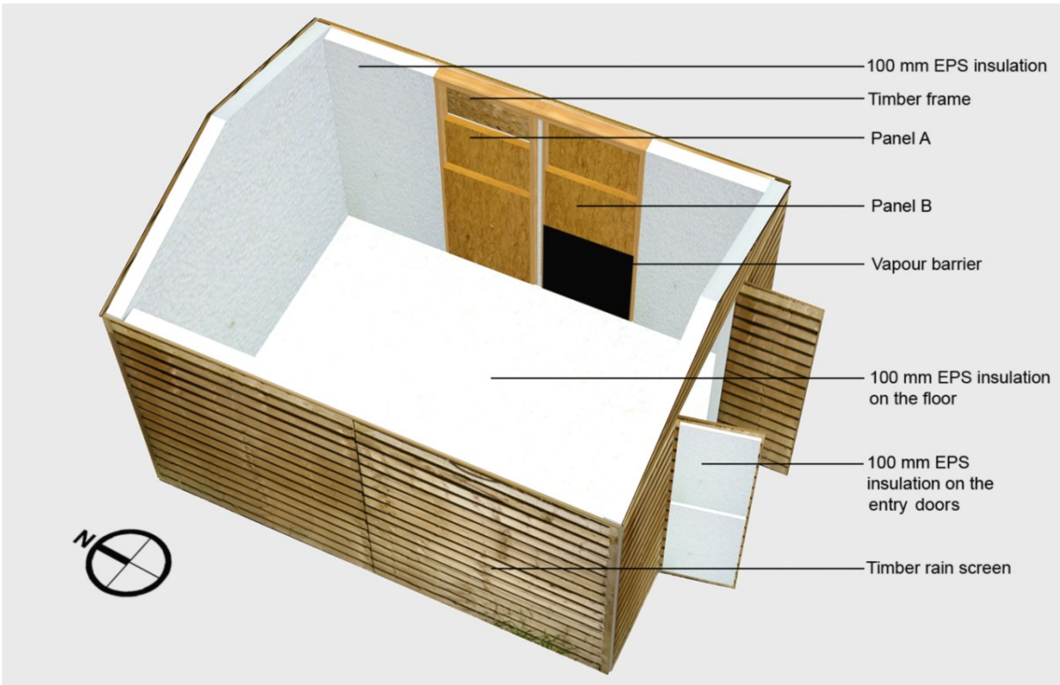

Fig. 6. 3-D view of the test building with the position of the test panels.

The east façade of the test building was completely shaded by other nearby buildings during the winter and 95% of the daytime during the summer. During the remaining 5% of the daytime in summer, the solar radiation was incident only on 5% of the eastern wall area incorporating EPS insulation and protected by a rain screen.

For this reason, the heat flux through the eastern wall was not affected by incident solar radiation. Hence, the eastern wall was suitable for assessing the U-value of the wall. The tests were conducted during January and February 2012. The averages of the maximum temperature, minimum temperature and mean temperature in the UK and Wales between 1910 and 2011 for the test months [26] are shown in Table 1. The mean temperature condition in Wales is not significantly different from the mean temperature condition in the UK and, thus, can be considered as representative of the UK climate. Although rainfall in Wales and Scotland is the highest in the UK, this was not relevant for the tests because a rain screen was used.

Table 1. Average external temperatures (temp) in the UK and Wales during January and February, between 1920 and 2011.

	Maximum temp in the UK (°C)	Maximum temp in Wales (°C)	Mean temp in the UK (°C)	Mean temp in Wales (°C)	Minimum temp in the UK (°C)	Minimum temp in Wales (°C)
January	5.9	6.4	3.24	3.8	0.6	1.2
February	6.3	6.5	3.4	3.8	0.5	1.0

3.4 Instrumentation of the test building and the test panels

The relative humidity and temperature in the test building were set to the required test level by a shielded convective heater with a thermostat and an evaporative industrial humidifier with a hygrostat.

The temperature and relative humidity sensors were installed at the following positions in Panel A and Panel B, as shown in Fig. 3: one sensor at the insulation-OSB interface, one in the middle of the insulation, and one on the outer surface of the PB inner lining. Two heat flux sensors were installed on the outer surface of the

PB or OSB inner lining of each panel, one at the centre of Panel A, and the other 300 mm away from the centre both vertically and horizontally. A water content reflectometer was placed between the OSB and the insulation in each of the wall panels to assess the moisture content in the insulation adjacent to the insulation-OSB interface. Because the water content reflectometer measures data in terms of soil moisture content, the data gathered from the water content reflectometer is used for qualitative comparisons of the presence of moisture content in the insulation between Panel A and Panel B. Fig. 7 shows the finished setup of the instrumented test panels.

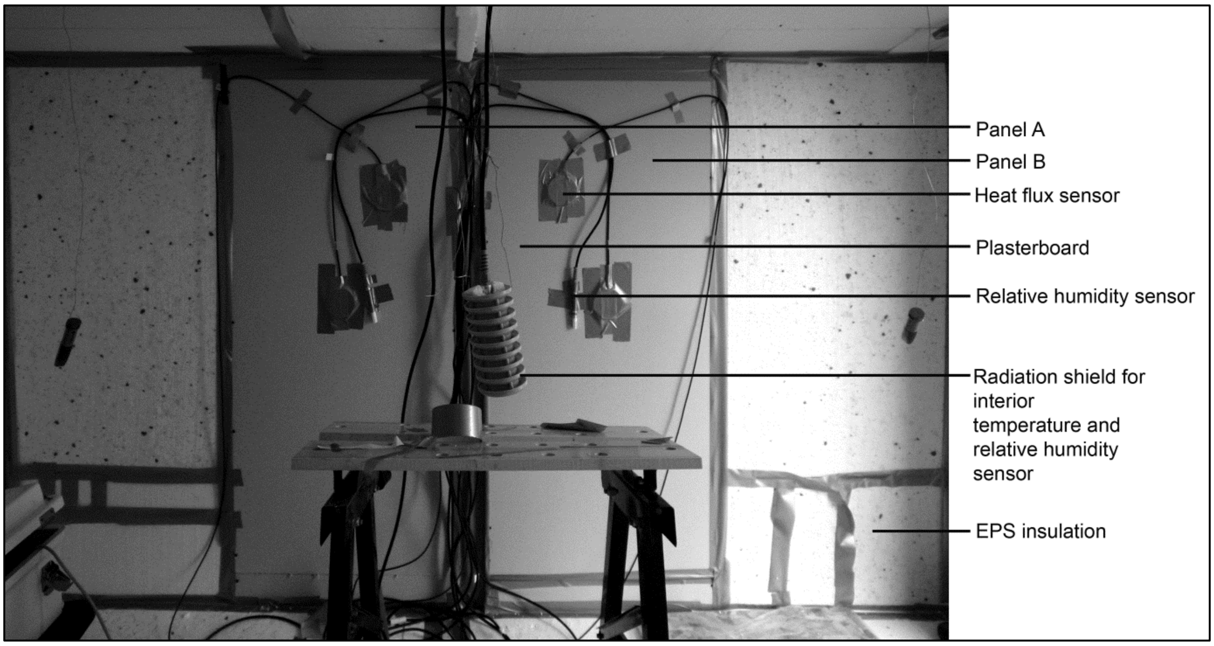

Fig. 7. The installation of the surface lining and the sensors.

3.5 Operational errors in heat flux measurement

The ISO 9869 outlines the following likely operational errors in in situ heat flux measurements [21]:

a. The error due to the calibration of the heat flux sensor and the temperature sensors is approximately 5%.

b. Random variation caused by differences in thermal contact between the sensors and the surface they are applied on can cause errors of approximately 5%.
c. Operational error due to the modification of isotherms by the placement of heat flux sensors, which may vary between 2% and 3%, is assumed as 2% for the present test.
d. Errors due to the variations in temperature and heat flux over time can be as much as 10% but can be reduced by taking data for a long period of time, keeping the variations in internal temperature low, etc. Because the test wall was not in direct contact with sunlight and the internal variations of temperature were low, the error was assumed to be approximately 5%.
e. Furthermore, another 5% error is introduced to the U-value measurement due to the temperature variations within the space and the difference between the air and radiant temperatures.

Thus, the total error in the U-value is calculated as the square root of sums of squares of the individual errors considered:

Total error in U-value = $\sqrt{5^2 + 5^2 + 2^2 + 5^2 + 5^2}$ = 10.2%

3.6 Experimental protocol

Two in situ tests were carried out in the timber frame test building, as described in subsection 3.3. The interior air velocity due to infiltration and convective air movement was 0.2 m/s. Table 2 shows the test set up and the duration of the two tests.

Table 2. The test setup and duration.

Tests	Wall Panel A	Wall Panel B	Inner lining in the panels	Dates of test	Test duration
Test 1	Without vapour barrier	With vapour barrier	Gypsum plasterboard (PB)	21.01.12-06.02.12	16 days
Test 2	Without vapour barrier	With vapour barrier	Oriented strand board (OSB)	11.02.12-27.02.12	16 days

The east wall of the test building contained wall Panel A without a vapour barrier and wall Panel B with a vapour barrier. Both panels were insulated with wood-hemp composite insulation. The interior temperature in the test building was maintained at 25 ± 3 °C. The relative humidity in the interior was kept at 90 ± 5% for two days (48 ± 3 hours) then decreased to 55 ± 5% for 4 days (96 ± 6 hours). Relative humidity values of 55 ± 5% can occur frequently in the interior of many houses in the UK [27]. Relative humidity of up to 90% can occur in and adjacent to bathroom and kitchen areas [28]. The ratio between the exposure times for relative humidity is based on the Nordtest [29] method, where the drying out time is twice the wetting time during exposure to relative humidity conditions. Furthermore, another 8 to 10 days of exposure to an interior humidity of less than 40% was included in the tests to assess the effect of decreasing the relative humidity on the drying of the insulation-OSB interfaces. The exterior boundary condition was the winter weather condition of the test site during January and February of 2012.

The tests were carried out as comparative tests. In both Test 1 and Test 2, emphasis was given to examining how identical composite hemp insulation materials in wall panels with and without a vapour barrier performed in response to similar hygrothermal boundary conditions. The performances of the panels were compared in terms of thermal transmittance, moisture conditions in the insulation and likelihood of mould spore germination.

The heat flux, water content, temperature and relative humidity data were logged every minute for the entire test period.

3.7 Assessment of thermal performance and mould growth conditions

The in situ U-values were calculated from the recorded experimental data using the average method according to ISO 9869, as shown in Equation [7]. The U-values of the panels were also calculated numerically based on the methods described in subsection 2.1. The mould growth condition was assessed in terms of parametric studies. For parametric studies, the temperature-relative humidity relationships were plotted from the collected data and compared to the conditions for mould spore germination in Sedlbauer's isopleths.

4. Results and discussion

4.1 Temperature and relative humidity

A thermographic image of the temperature distribution on the OSB inner surfaces of Panel A and Panel B are shown in Fig. 7. The thermographic image shows that the temperature distribution in the two panels has a similar pattern, with the upper part having a 0.5 °C higher temperature than the lower part. The interior and exterior temperature and relative humidity conditions for Test 1and Test 2, as running averages of every one hour for 16 days, are shown in Figs. 9 and 10, respectively.

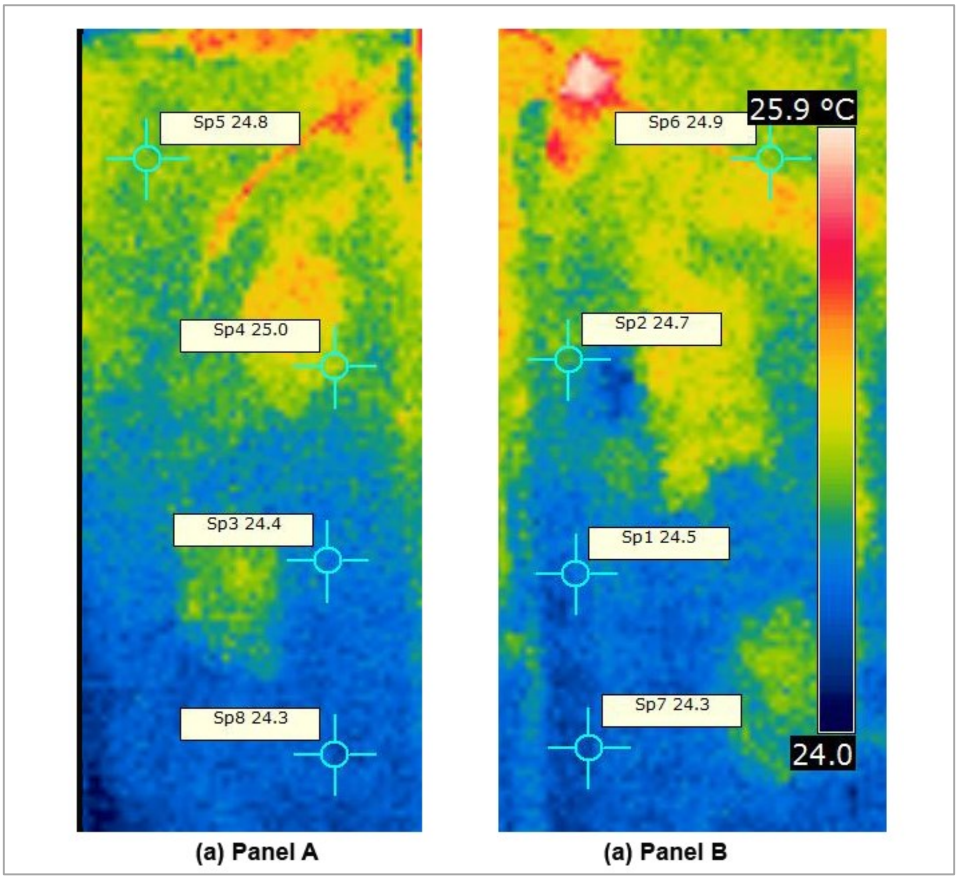

Fig. 8. Surface temperatures in the OSB inner lining, (a) Panel A and (b) Panel B.

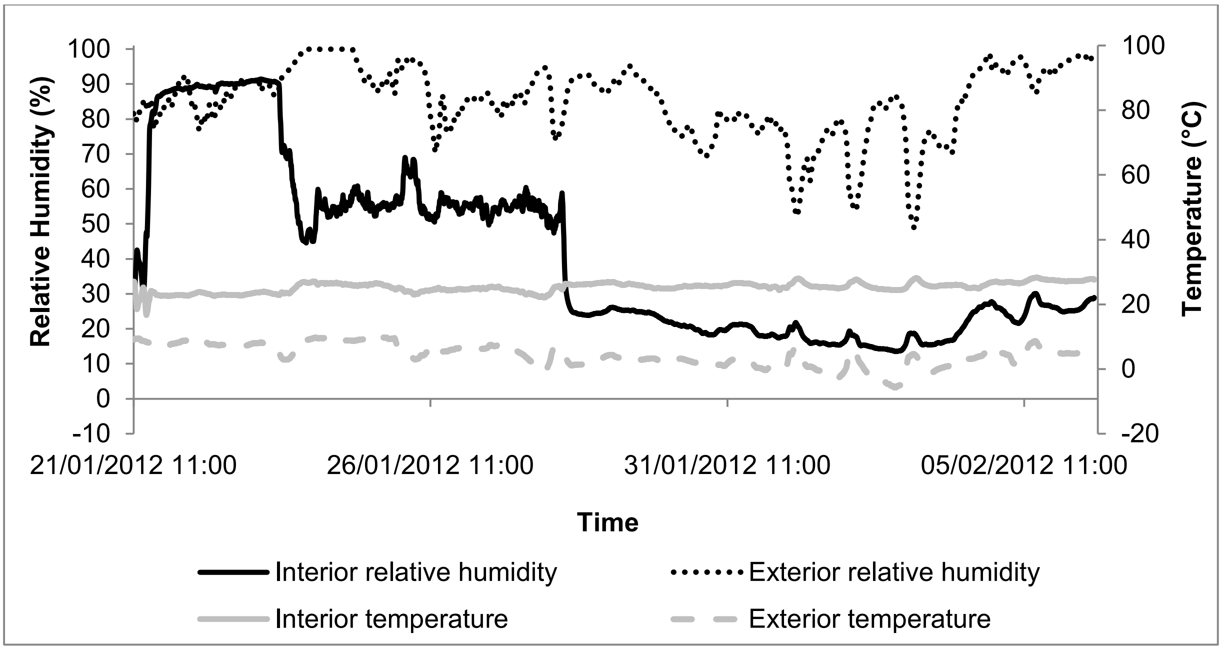

Fig. 9. Temperature and relative humidity during Test 1.

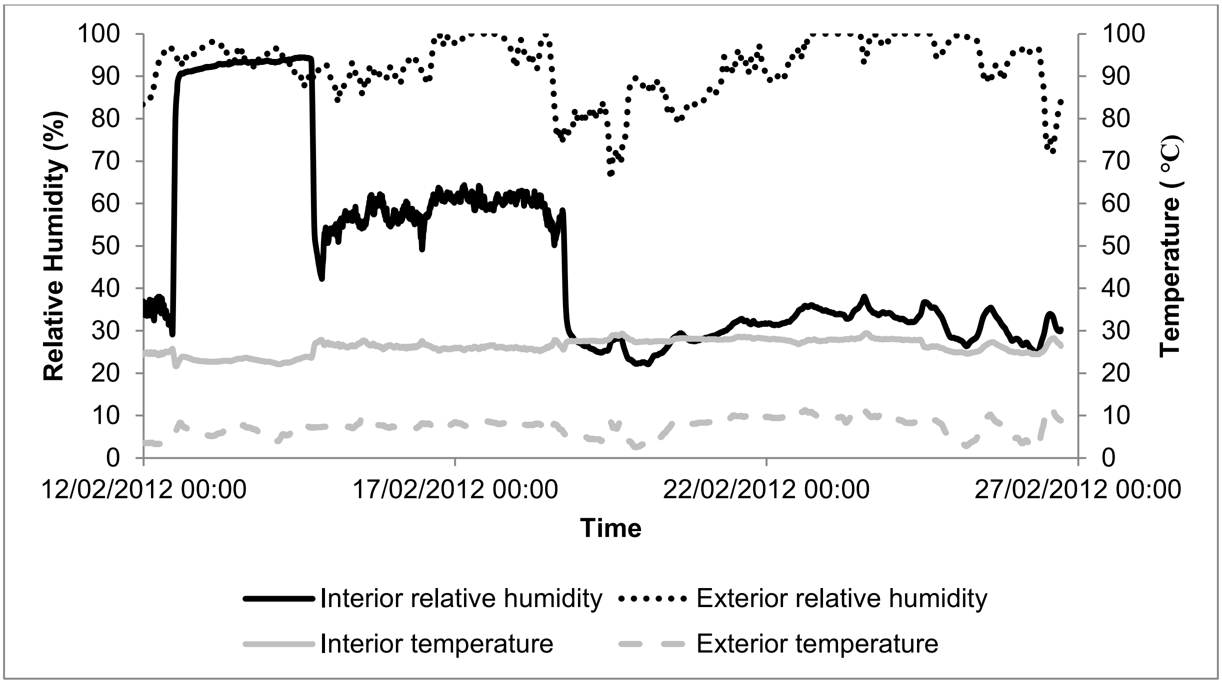

Fig. 10. Temperature and relative humidity during Test 2.

4.2 Heat flux and U-value

Figs. 11 and 12 show the heat flux and temperature differences between the internal and external ambient temperatures in the wall panels with and without a vapour barrier for Test 1 and Test 2.

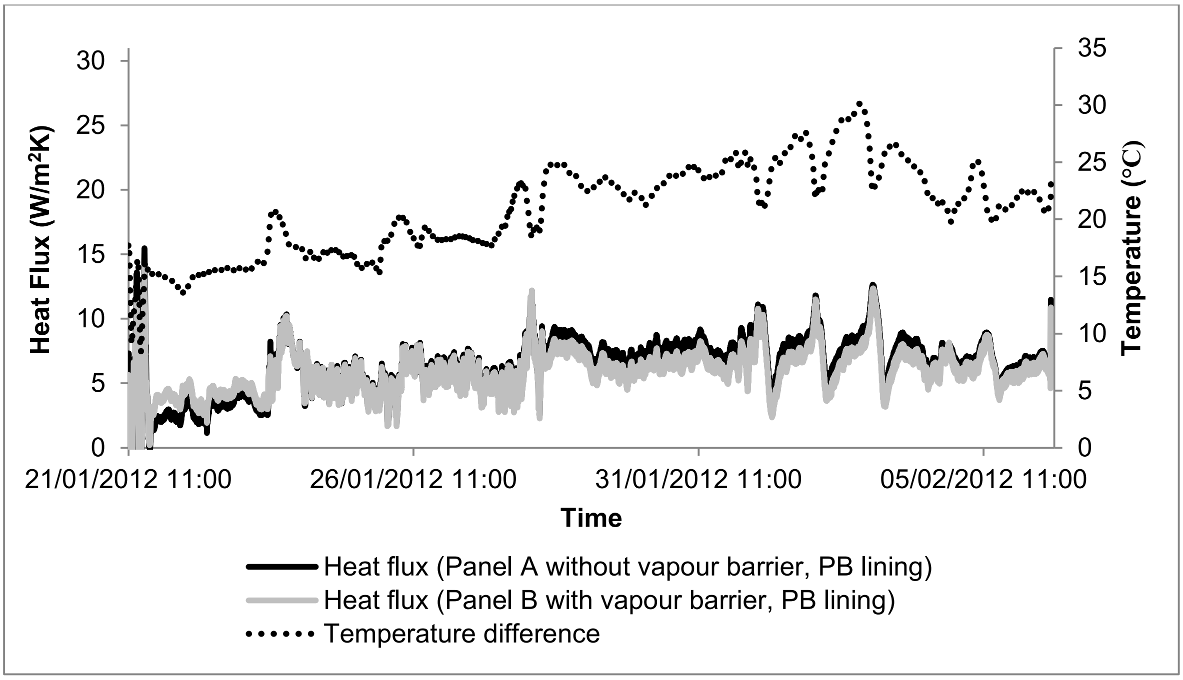

Fig. 11. Heat flux in panels with plasterboard lining during Test 1.

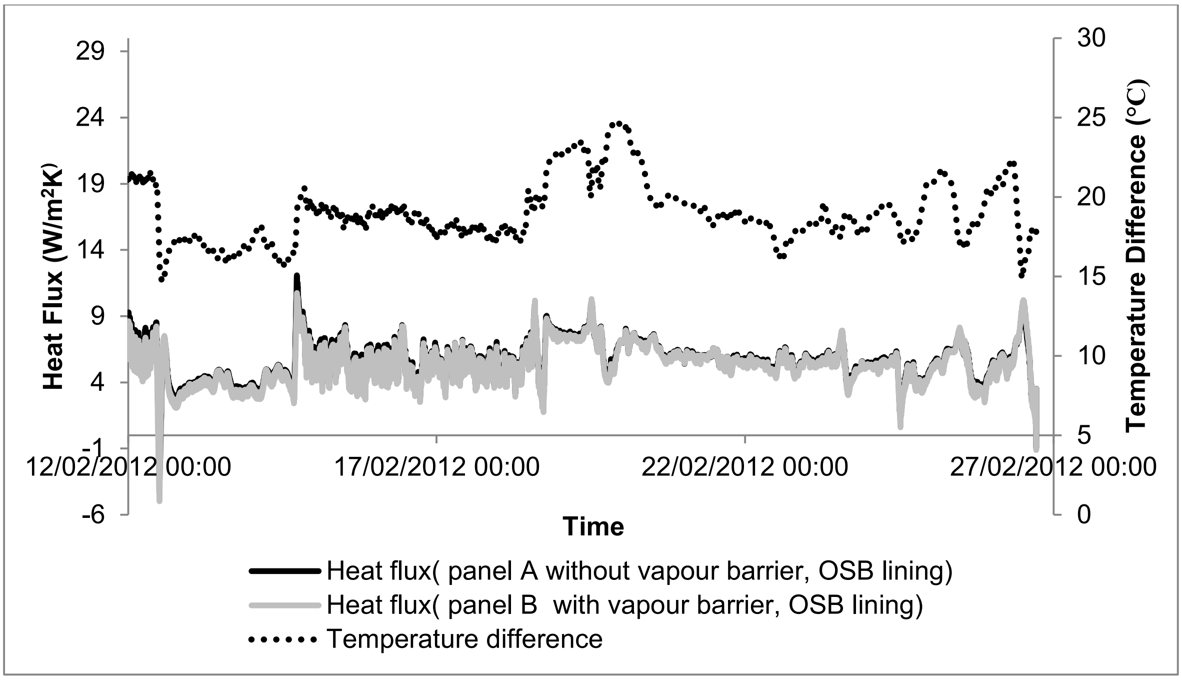

Fig. 12. Heat flux in panels with plasterboard lining during Test 2.

The calculated U-values of Panel A and Panel B in a dry condition, with and without considering the effect of thermal bridging through the timber studs, are shown in Fig. 13.

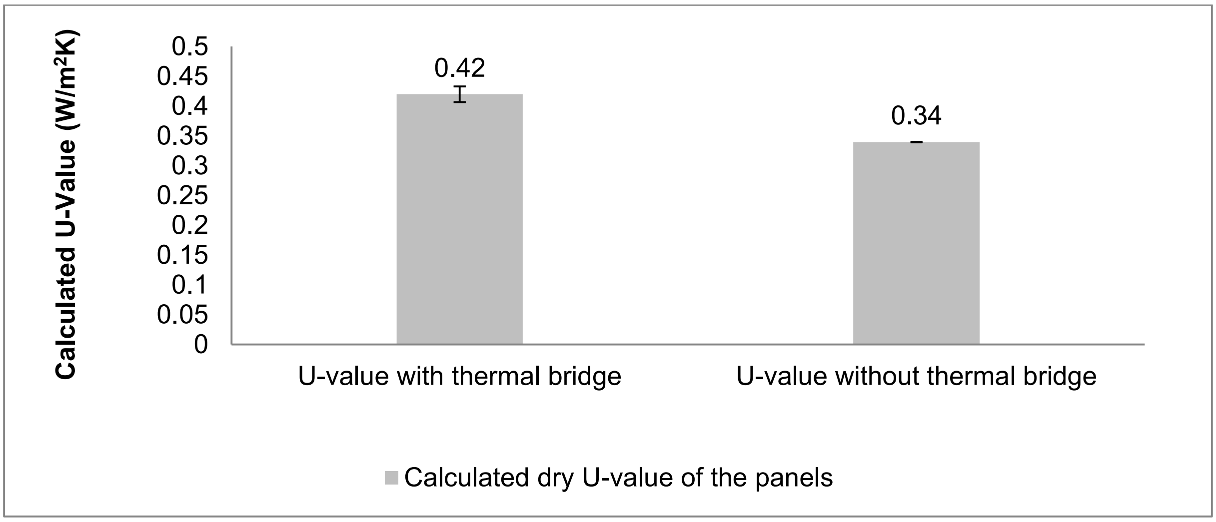

Fig. 13. Calculated U-values of wall Panel A and B in a dry condition with error bars.

One of the objectives of the study was to determine the in situ U-value of the wall panels insulated with wood- hemp composite and to assess the difference in the U-value when a vapour barrier is used and when the barrier is not present. The equivalent U-values of Panel A and Panel B during Test 1and Test 2 are shown in Figs. 14 and 15, respectively.

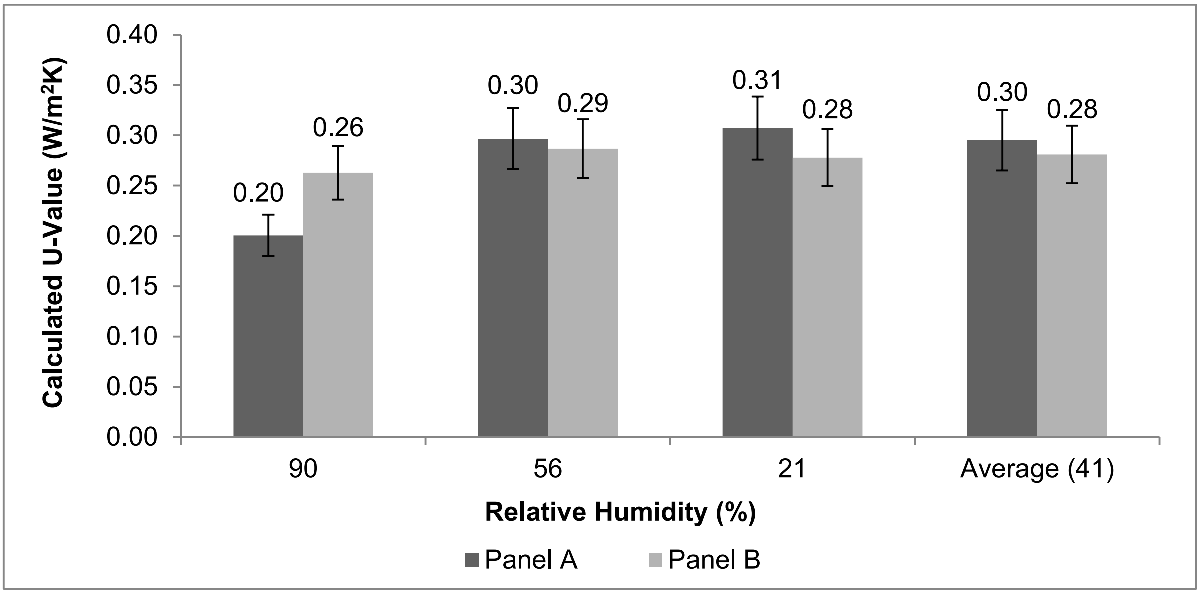

Fig. 14. Calculated equivalent U-values with error bars during Test 1.

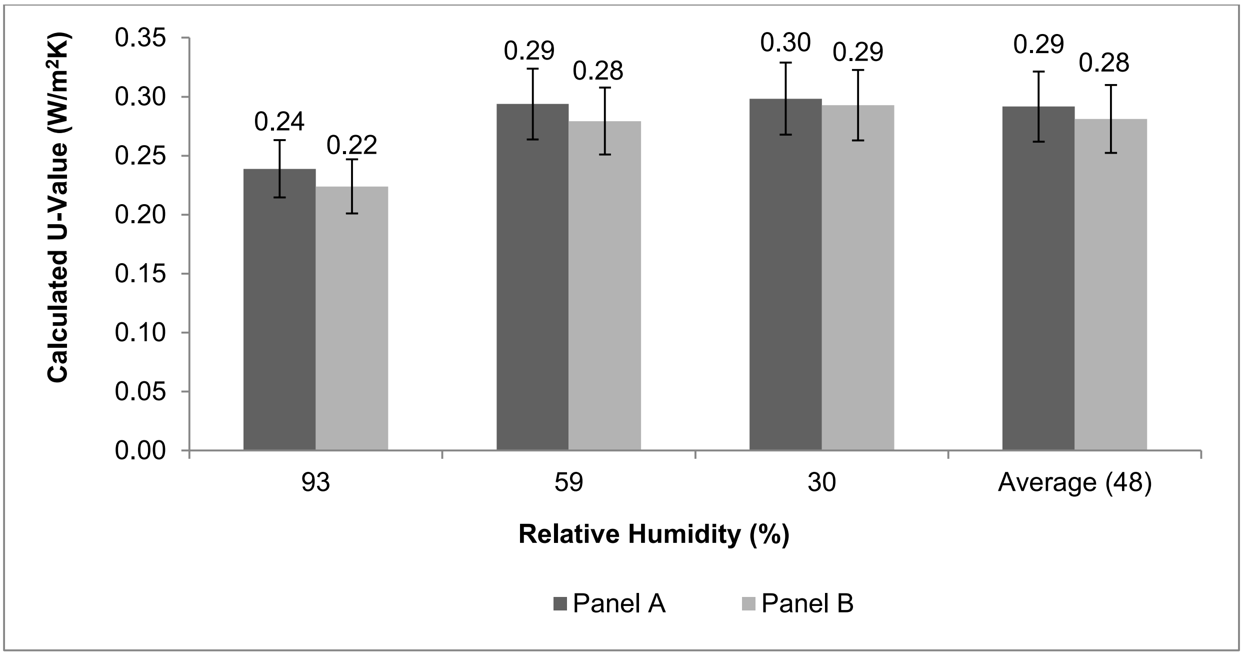

Fig. 15. Calculated equivalent U-values with error bars during Test 2.

For Test 1 in the winter with an internal lining of PB, the average U-value of the vapour open panel was 7.1% higher than that of the panel with a vapour barrier. For

Test 2 in the winter with an internal lining of OSB, the average U-value of the vapour open panel was 3.6% higher than that of the panel with a vapour barrier.

For Test 1 and Test 2, the measured equivalent U-values of Panel A were 28.6% and 30% lower, respectively, than the numerically determined U-values of the panel based on the manufacturers' declared thermal conductivity when the effect of thermal bridging was taken into account. When the effect of thermal bridging was not accounted for, the measured equivalent U-values of Panel A were 14.7% and 11.8% lower than the calculated U-value for Test 1 and Test 2, respectively.

For Test 1 and Test 2, the measured equivalent U-values of Panel B were 33.3% lower than the numerically determined U-values of the panel based on the manufacturers' declared thermal conductivity when the effect of thermal bridging was taken into account. When the effect of thermal bridging was not accounted for, the measured equivalent U-values of Panel B were 17.7% lower than the calculated U-value for both Test 1 and Test 2.

The variations in U-value for the panels with and without a vapour barrier in the aforementioned cases are not significant in terms of their effect on the heat loss. The significance is further lessened when the 10.2% error in the U-value measurement is considered. These findings reflect Nicolajsen's (2005) findings on cellulose insulation where there was no difference in the U-value in wall panels with and without a vapour barrier.

During high internal relative humidity of 90% and 93%, the measured U-value of Panel A is lower than its average U-value by 33.3% and 17.2% for Test 1 and Test 2, respectively. For the same interior relative humidity, the measured U-value of Panel

B is lower than its average U-value by 7.1% and 21.4% for Test 1and Test 2, respectively.

During the period of high interior relative humidity of 90% and 93%, the temperature difference between the interior and the exterior drops (Fig. 10) as the increased interior moisture content potentially absorbs heat from the interior due to its high heat capacity and possible phase change potential. As a result, the drop in heat flux was disproportionate to the temperature difference between the exterior and interior (Fig. 11). Thus, the U-values of the panels decreased during high interior relative humidity. The secondary cause of the change in U-value at high interior relative humidity is applicable to Panel A only. Because Panel A is vapour open, moisture adsorption by the wood-hemp insulation and enthalpy flow by moisture movement along the thermal gradient is highly likely. The heat flux through the wall can be a function of moisture dependant thermal conductivity of the insulation, modified thermal diffusivity and heat capacity induced by moisture adsorption, enthalpy flow and phase change due to moisture diffusion along the temperature gradient. A similar phenomenon was also observed by Labat et al. [13]. For the above reasons, it is plausible that the heat flux could either increase or decrease in a vapour open panel in high interior relative humidity based on the dominance of moisture movement or adsorption. The surface-mounted heat flux sensors may not register the phase change of the diffused water in the insulation-OSB interface of Panel A. This phenomenon was identified and explained by Latif et al.[12].

4.3 Relative humidity and prediction of mould growth

Figs. 16 and 17 show the relative humidity and soil moisture content equivalent in the wood-hemp-OSB interfaces of Panel A and Panel B for Test 1 and Test 2, respectively.

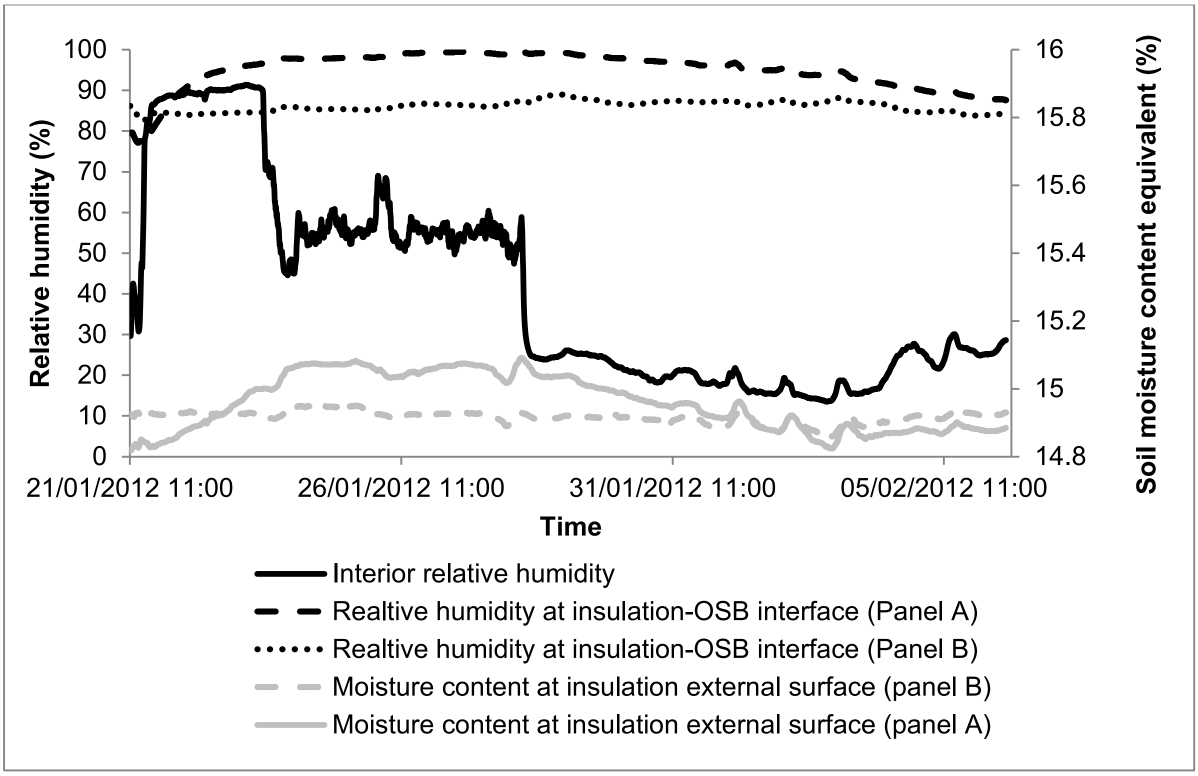

Fig. 16. Relative humidity and soil moisture content equivalent in the insulation-OSB interfaces during Test 1.

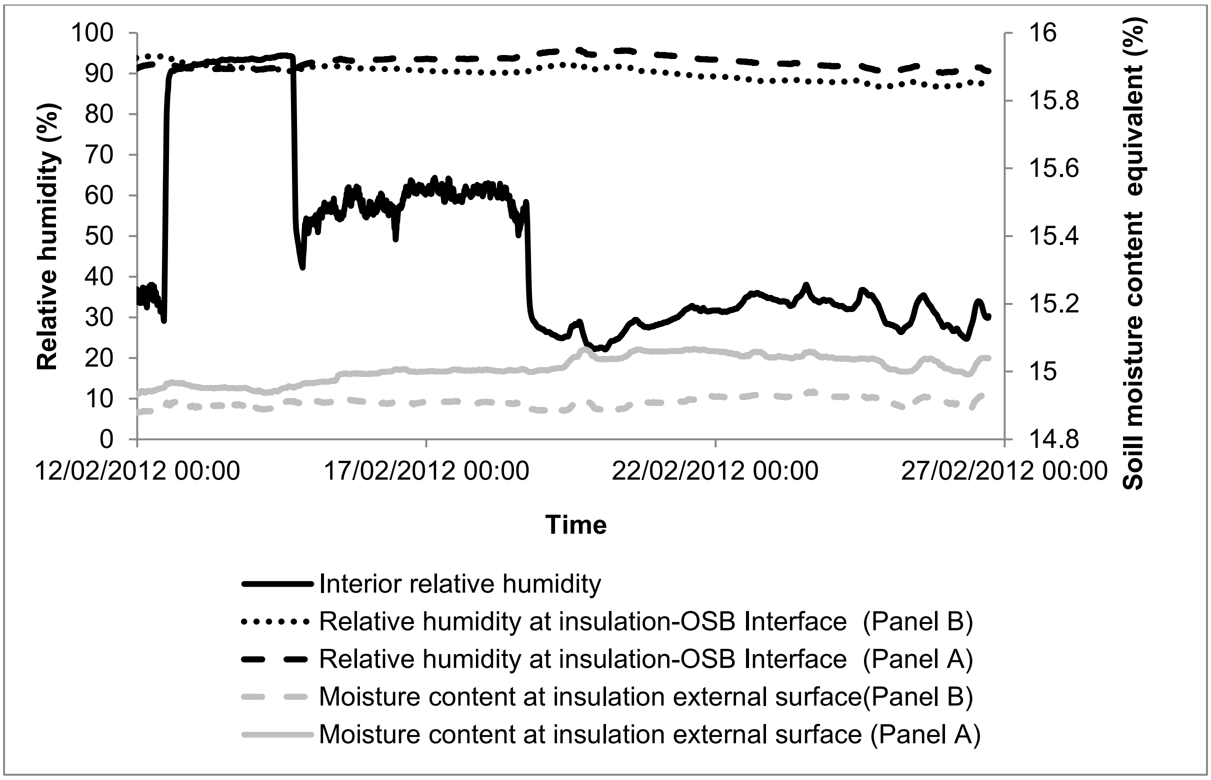

Fig. 17. Relative humidity and soil moisture content equivalent in the insulation-OSB interfaces during Test 2.

The peak increases of relative humidity in Panel A are 12.2% and 4.6% higher compared to that in Panel B during Test 1 and Test 2, respectively. In all cases, the relative humidity in the insulation-OSB interface is more than 85% for most of the time. The peak increases of soil moisture content equivalent in Panel A are 1.2% and 1% higher compared to that in Panel B during Test 1and Test 2, respectively.

During the tests, a delay is seen in terms of wetting and drying of the insulation-OSB interface in response to the change in relative humidity. The delay in wetting can be explained in terms of the adsorption kinetics and the moisture adsorption capacity of wood-hemp insulation that can decrease the moisture diffusivity in dynamic hygrothermal conditions. The delay in drying can be explained in terms of the desorption kinetics, or the moisture desorption capacity and the hysteresis effect in wood-hemp insulation during the adsorption and desorption process. Furthermore, both the relative humidity and the soil moisture content equivalent in Panel A decreases at a faster rate during Test 1 than during Test 2. This may be explained in terms of the relative vapour diffusion resistance factors of plasterboard and OSB (Table 3).

Table 3. Vapour diffusion resistance factors of Plasterboard and OSB [30].

Material	Vapour Diffusion Resistance Factor (Dry), μ	Vapour Diffusion Resistance Factor (Wet), μ
Gypsum Plasterboard	10	4
Oriented Strand Board (OSB)	50	30

The vapour diffusion resistance factor of gypsum plaster board is 80% and 86.7% lower than that of OSB for dry cup and wet cups tests, respectively. This implies that, compared to OSB, plasterboard allows moisture to diffuse at a faster rate.

For Test 2, the initial moisture content in the external surface of Panel A was high with a corresponding relative humidity value of 91%. The moisture content continued increasing until it reached a value equal to the peak value of Test 1. However, unlike Test 1, the moisture content did not decrease in low internal relative humidity for two plausible reasons. First, the average value of low internal relative humidity was 30% during Test-2 while the corresponding value was 21% during Test 1. Second, hysteresis in wood-hemp insulation combined with the high vapour diffusion resistance factor of the OSB inner lining may have contributed to the delay in moisture release.

Thus, compared to OSB, the lower vapour diffusion resistance factor of plasterboard may reduce the risk of moisture accumulation in the critical interfaces of vapour open wall panels in dynamic hygrothermal boundary conditions.

Figs. 18 through 20 present the hygrothermal conditions (the plot of temperature versus relative humidity) in the insulation-OSB interfaces of Panel A and Panel B in conjunction with the Sedlbauer's isopleths for substrate class 1 during Test 1and Test 2.

In terms of the LIM I isopleth, Figs. 18 and 20 show that the hygrothermal conditions in the insulation-OSB interface above 5 °C temperature, in both Panel A and Panel B during Test 1and Test 2, are over the LIM I isopleth. This implies that, in terms of the LIM I isopleth, the insulation is susceptible to mould spore germination in both Panel A and Panel B.

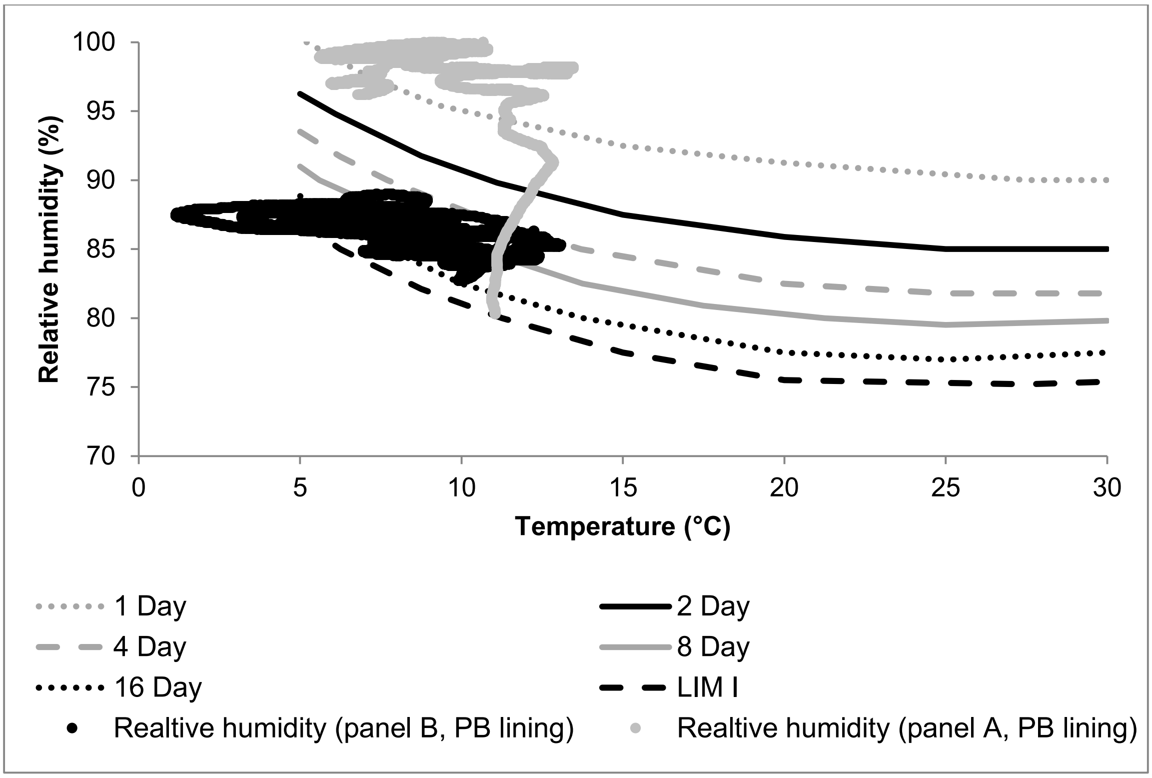

Fig. 18. Insulation-OSB interface conditions against the Sedlbauer's isopleth during Test 1.

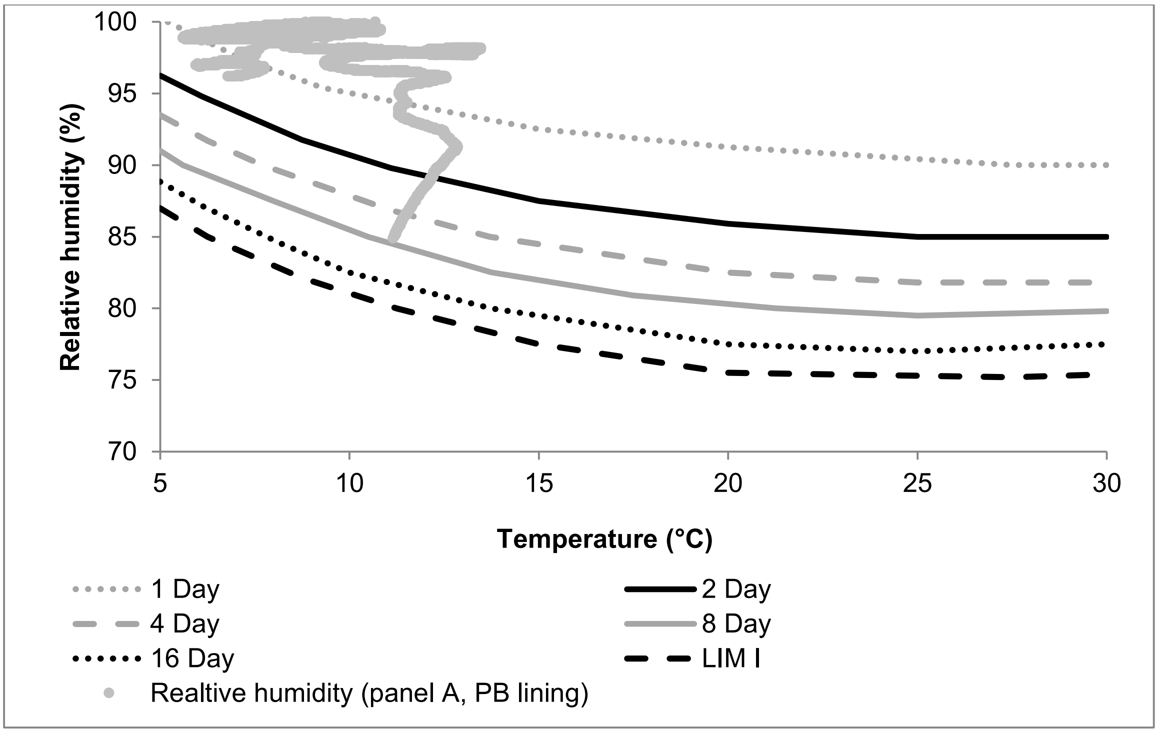

Fig. 19. 11 day conditions of the insulation-OSB interface condition against Sedlbauer's 8-day isopleth line during Test 1.

Fig. 18 also shows that during Test 1, the hygrothermal condition in Panel A is mostly concentrated in the upper ranges of the plot. This is further analysed and presented in Fig. 19 which shows the continuous 11 day hygrothermal condition at the hemp-OSB interface in Panel A with PB inner lining for Test 1. Based on the Sedlbauer's germination isopleth for 8-day exposure, the germination of mould spores seems plausible as the duration of the hygrothermal condition exceeded 8 days.

Fig. 20 illustrates the hygrothermal condition at the insulation-OSB interfaces during Test 2 in Panel A and Panel B.

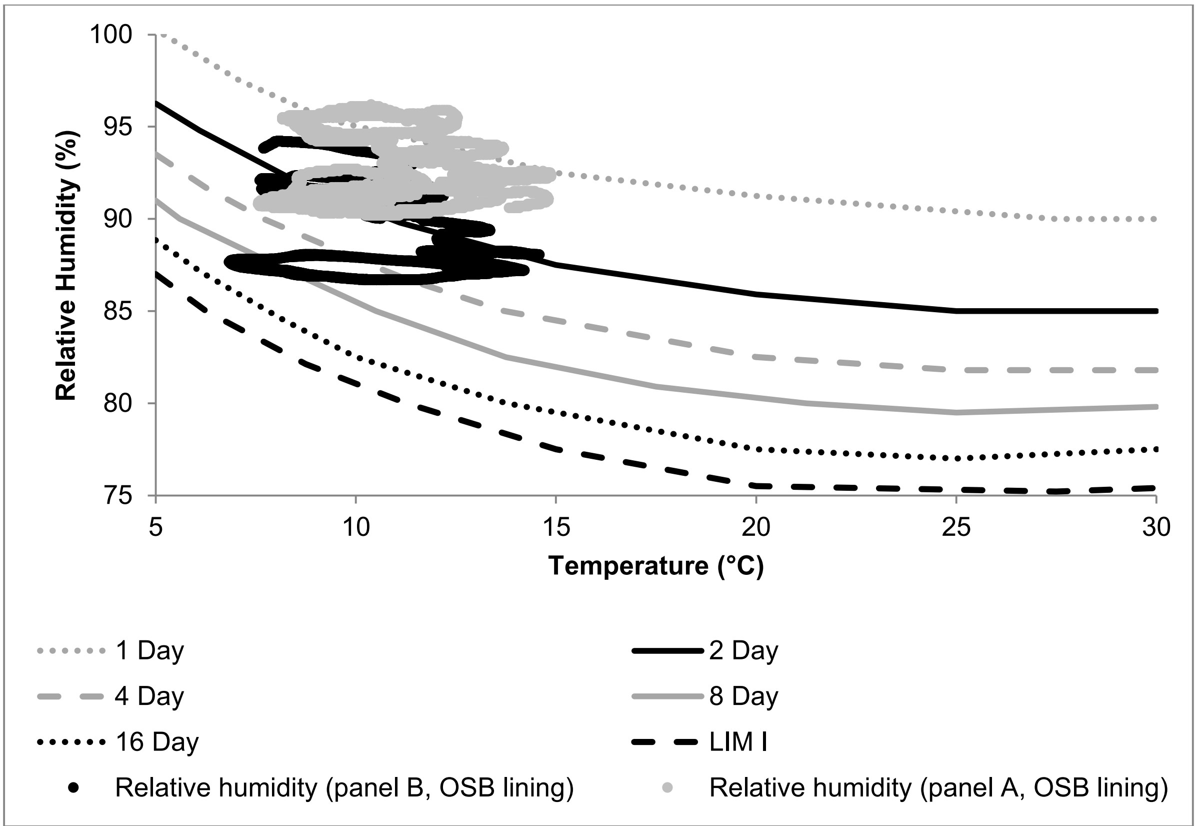

Fig. 20. Insulation-OSB interface condition against Sedlbauer's isopleth during Test 2.

The hygrothermal conditions at the insulation-OSB interface in Panel A are always over the 4 day isopleth, and the hygrothermal conditions at the insulation-OSB interface in Panel B is mostly over the 8 day isopleth. The duration of the test was 16 days, exceeding 4 and 8 days, respectively. Hence, the hygrothermal conditions in both cases are favourable to mould spore germination. However, mould spore germination is likely to occur earlier in Panel A.

During Test 2, the relative humidity at the insulation-OSB interface increased to approximately 99% in Panel A, which is near the condensation condition. However, condensation will only occur when the adjacent surface temperature is equal to or lower than the dew point temperature of the moist air. The wall panels were reasonably airtight, and therefore the moisture movement inside the insulation may have been caused by vapour diffusion and the temperature gradient along the wall sections rather than by any convective flow due to leakage of room air through the wall panels. On the other hand, if condensation occurs at a rate lower than the water absorption coefficients of either the insulation or the OSB, the water will be absorbed by the insulation or the OSB. When the insulation samples were dismantled, on visual observation, no trace of wetness was found on the insulation or on the OSB surface. Either no condensation occurred or the condensed water was absorbed by the insulation or the OSB.

5. Conclusions

This paper has focused on the assessment and comparison of the in situ hygrothermal performance of a wood-hemp composite insulation in panels with and without a vapour barrier, with identical hygrothermal boundary conditions in a full scale test building. Plasterboard and OSB inner linings were used during Test 1 and Test 2, respectively. The heat flux through the wall panels with and without a vapour barrier was assessed and compared in terms of U-values. The average U-values of wall Panel A (without a vapour barrier) were 0.30 and 0.29 W/m^{2}K for the plasterboard and OSB inner linings, respectively. The average U-values of wall Panel B (with a vapour barrier) were 0.28 W/m^{2}K for both the plasterboard and OSB inner linings. The equivalent U-value of Panel A was higher than the equivalent U-value of Panel B by 7.1% and 3.6% for the plasterboard and OSB inner linings, respectively. The in situ U-values were always lower than the U-values calculated from the manufacturers' declared thermal conductivity value. In terms of moisture management, the rate of both wetting and drying was faster in the insulation interface when plasterboard was used as the inner lining in the vapour open wall panel. This was plausibly due to the lower vapour diffusion resistance factor of the plasterboard compared to that of the OSB. A delay was seen in the insulation interface in responding to changes in the internal relative humidity due to the moisture adsorption-desorption capacity, sorption kinetics and hysteresis effect of the wood-hemp insulation. With regards to the Sedlbauer's isopleths of mould spore germination, the inclusion of a vapour barrier did not ensure a hygrothermal condition to deter mould spore germination. The hygrothermal condition at the insulation-OSB interface of Panel A was more favourable to mould spore germination than that of Panel B. Therefore, for the parametric prediction of mould spore germination based on experimental hygrothermal data, antifungal treatment of the wood-hemp composite insulation may be suggested. However, visual inspection of the dismantled insulations and the OSB panels did not suggest any onset of mould growth.

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