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Performance of Bio-based Products for Interior Insulation of Solid Masonry Walls

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Abstract. A recent Danish project has studied the possibilities of using bio-based materials for interior insulation of solid brick walls, without the use of a vapour barrier. The purpose was to give indications of the possibility to use hygroscopic insulation material in positions as interior insulation, where it is known to be potentially vulnerable to moisture accumulation. Three bio-based thermal insulation materials were investigated: loose-fill cellulose insulation (two variants) and hemp fibre insulation commercially available in Denmark. The hygrothermal performance of the three insulation materials for internal retrofitting purposes was investigated in a large-scale experiment comprising several solid masonry walls. The test walls were built in an outdoor test field north of Copenhagen, and exposed to a controlled indoor climate. The experiments were conducted over 1 year and 9 months where moisture measurements were done in several locations within the walls, including the interface between insulation and masonry, as well as in embedded wooden components such as a beam end and a wall plate. The paper illustrates the results from experiments with or without a hydrophobizing treatment on the exterior surface as causes of moisture content in potentially critical places in the walls. Finally, some results from mould growth determinations are reported. Generally, high levels of moisture content were found in the interior insulation, particularly for non-hydrophobized walls, but critical mould growth conditions were found only in the case of one of the tested materials.

1. Introduction

State-of-the-art

There is an increasing interest in using bio-based insulation materials in Denmark. Internal insulation is considered a risky solution, and it is of interest to know if bio-based insulation materials such as cellulose and hemp can be used in traditional buildings, which are often made with solid brick walls. As the wall gets colder, the heat flow is reduced, and the temperature gradient is reduced in the masonry. These factors may increase the risk of high moisture levels, which can lead to moisture-induced damage such as fungal growth or wood decay.

For retrofitting with internal insulation, mineral wool and vapour barriers have previously been the most frequently used solution in Denmark. However, this can lead to fungal growth due to solar-driven vapour flow from the outside towards the inside during periods of alternating rain and sun exposure, and insufficient tightness. Different types of foam plastics such as polyurethane, polyisocyanurate and phenolic foam are all examples of diffusion-tight plastics that have been studied in precursors to the current project, and the results have been mixed [1] and [2].

Recent changes in internal insulation strategies have seen a shift from diffusion-tight systems with vapour retarders or based on vapour-tight insulation material to diffusion-open or capillary active insulation systems. The idea is that rather than potentially trapping moisture in diffusion-tight systems, it should be possible to allow redistribution of moisture from a condensation zone towards the interior, reducing the risk of fungal growth. These insulation materials include calcium silicate and aerated concrete [1] and [5]. A comprehensive literature review showed that there is a lot of disagreement in the literature about which types of internal insulation are best suited to what situations, and if additional measures are required [1]. Diffusion-open systems have shown to perform slightly better than those with tight insulation [1].

Although internal insulation is considered risky and recent studies with inorganic insulation material reveal unacceptable RH levels and sometimes fungal growth [1], several studies have shown that it is possible to insulate historic buildings using biobased insulation materials, e.g. [2], [3] and [4]. However, all studies with good hygrothermal performance had the interior insulation combined with exterior plaster and paint, which could have acted as rain protection, and/or there was a low indoor humidity load. The current project wanted to study the possibility to apply interior insulation to masonry that does not have exterior render or paint.

Different types of additives can be added to bio-based insulation and to the original masonry, such as flame retardants and hydrophobizing agents. Flame retardants may also prevent mould growth.

Scope

The study reported in this paper had the purpose to evaluate the hygrothermal performance of three bio-based, diffusion-open insulation systems. It was desired to see if critically high moisture contents and mould growth could be avoided when the insulation is very hygroscopic, highly vapour permeable, and a vapour retarder is omitted, and when the organic material is potentially susceptible to biological decay. Furthermore, it was a purpose to determine if hydrophobization of the exterior surface to decrease the absorption of wind-driven rain (WDR) could reduce the moisture content to acceptable levels in the walls with bio-based interior insulation.

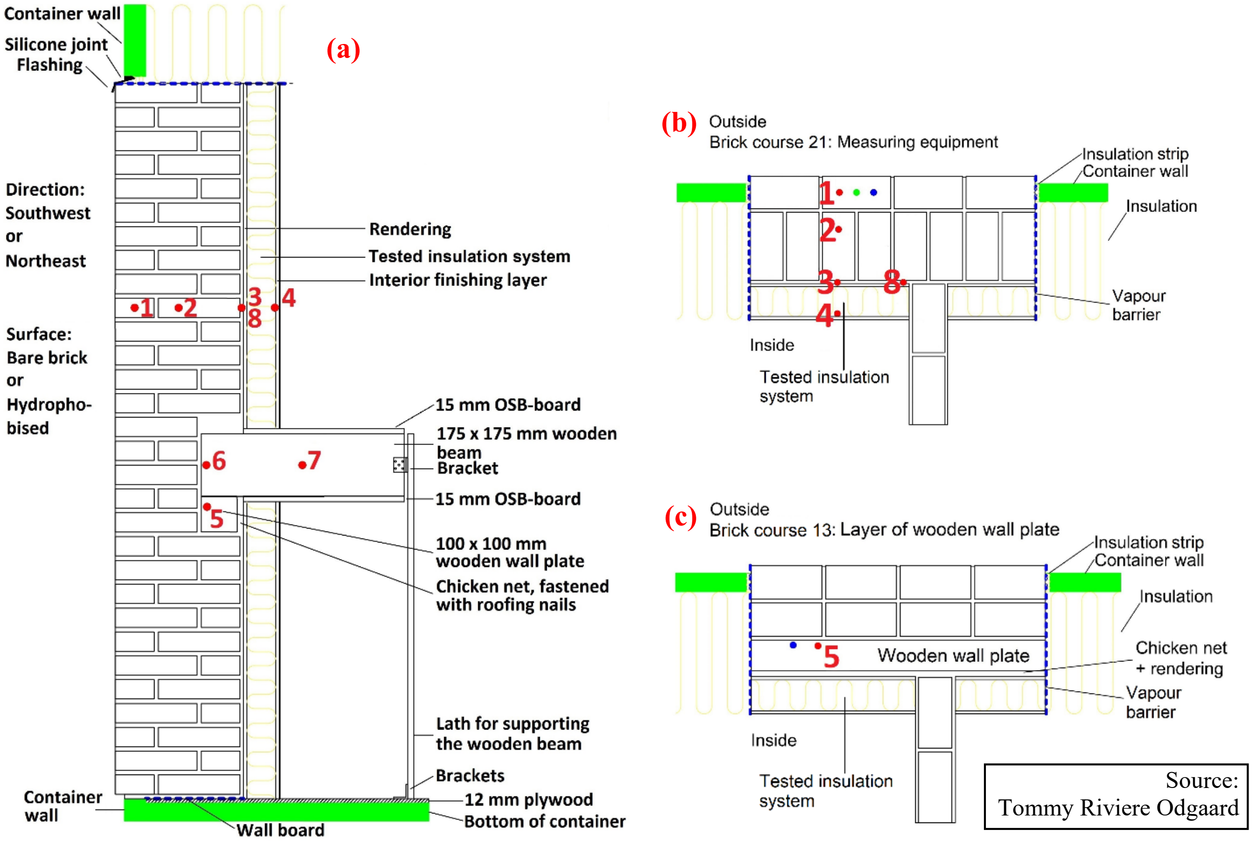
2. Methods

Experimental setup

Two 40-foot insulated reefer containers labelled “G” and “X”, were used in the experimental setup, see Figure 1. A total of 24 solid masonry test walls with dimensions (H x W x D) 1987 x 948 x 358 mm (1 1/2 stone thick with 10 mm interior rendering) were placed in cut-outs in the side walls of the containers. On the inside, a 3-dimensional configuration was made to mimic a wooden floor supported by a 175 x 175 mm wooden beam that was embedded 100 mm into the masonry wall. The beam was again supported by a 100 x 100 mm embedded wooden wall plate. The wood elements were made of ordinary construction timber (Pomeranian Pine Wood). The test walls were made using yellow soft-moulded bricks and 7.7% lime-adjusted mortar, to replicate the conditions found in Danish historical buildings from 1850-1930. The walls had an interior render of lime mortar. The experimental setup was built in August-September 2014 and has previously been used for testing inorganic interior insulation systems [5]. The bio-based systems were installed in the autumn of 2020, and measurements began in December 2020.

Source: Nickolaj Feldt Jensen and Tommy Riviere Odgaard

Figure 1. The experimental setup. (a): Test containers. (b) Embedded wooden wall plates. (c) Sensors in masonry bricks. (d) Embedded wooden beam ends. (e) Hemp insulation, and (f) Cellulose insulation being installed.



Source: Tommy Riviere Odgaard

Figure 2. Test stand configuration. (a) Vertical section of a test wall. (b) Horizontal section through the 21st course of bricks. (c) Horizontal section through the 13th course of bricks.

Configurations for wall insulation

This paper presents the results from 13 test walls. Wall configurations of four insulation systems were tested as listed in Table 1: 1) Hemp fibre insulation matt (*Hemp*), 2) and 3) two loose-fill cellulose insulation systems, *Cellulose1* and *Cellulose2*, and 4) a traditional system of mineral wool and vapour barrier (*MW*). Five of the exterior masonry walls were treated with a silane/siloxane-based hydrophobizing cream, while the exterior surface of the other brick walls was left untreated.

The compounds that were used in the insulation materials as flame retardants were the following:

- *Hemp*: 10 weight-% sodium carbonate Na_2CO_3.
- *Cellulose1*: 5.1-weight-% aluminium hydroxide $Al(OH)_3$, and 4.9-weight-% boric acid, H_3BO_3
- *Cellulose2*: 8 weight-% aluminium hydroxide, $Al(OH)_3$, and 4 weight-% boric acid, H_3BO_3.

Equipment for measuring

Temperature and relative humidity were recorded every 10 minutes in locations shown in Figure 2 with red dots. Sensors were also used to measure DC electrical resistance in embedded wooden dowels, marked with blue dots in Figure 2, and converted into moisture content. Furthermore, the indoor climate of each container as well as the outdoor climate were monitored at the same intervals. Weather data was obtained from a weather station near the test containers.

Table 1. Wall configurations and properties used in the field study. Material properties: Density, ρ; thermal conductivity, λ; water absorption coefficient, A_w, thickness, d; thermal resistance, R; and vapour diffusion resistance, Z. While walls G3, G14, and X5 were kept as uninsulated base walls for reference, interior insulation was applied to the base walls in other cases.

Wall ID	Material layers (listed from the exterior side)	ρ [kg/m^3]	λ_{dry} [W/(m·K)]	μ_{dry} [-]	A_w [kg/(m^2·s^{½})]	d [mm]	R [m^2·K/W]	Z [m^2·s·Pa/kg]
Existing base wall	Yellow brick	1643	0.600	16.9	0.278	348	0.58	3.0E+10
	7.7% lime mortar	1243	0.440	22.4	0.390	10	0.02	1.1E+09
G1_MW+VB_SW	Mineral wool	37	0.04	1	0	100	2.50	5.1E+08
	Vapour barrier							7.1E+11
	Gypsum board	850	0.2	10	0.277	13	0.07	6.6E+08
G2_Hemp+H_SW G5_Hemp_SW X2_Hemp+H_SW X3_Hemp_SW	Hemp fibre Fibre gypsum board	35 1133	0.039 0.341	2 14.2	0.032 0.057	170 13	4.36 0.04	1.7E+09 9.3E+08
G6_Cellulose1+H_SW G7_Cellulose1_SW G10_Cellulose1_NE G11_Cellulose1+H_NE X6_Cellulose1+H_SW X7_Cellulose1_SW	Cellulose1 Fibre gypsum board	46 1133	0.039 0.341	1 14.2	0.56 0.057	170 13	4.36 0.04	8.6E+08 9.3E+08
G8_ Cellulose2+H_SW	Cellulose2	43.5	0.039	1.2	0.56	170	4.36	1.0E+09
G9_ Cellulose2+H_NE	Fibre gypsum board	1133	0.341	14.2	0.057	13	0.04	9.3E+08

+H: hydrophobization, X: container X with 60% indoor RH, G: container G with varying indoor RH according to EN/ISO 13788 class 2, SW: Southwest, NE: Northeast.

Boundary conditions

The indoor climate in container "X" was maintained at 20 °C and 60 % RH, while in container "G", the RH was adjusted over the course of the year according to the upper limit for indoor humidity class 2 according to EN/ISO 13788 [7].

The prevailing wind direction in Denmark is southwest, which is therefore the most important orientation for WDR. The test walls were placed to face either southwest or northeast.

On-site fungal growth tests

Mycometer surface tests [6] were used for quantitative measurement of fungal growth, and swab testing was used to determine the fungal species. The masonry/insulation interface was the focus of this sampling. One and a half years after the start of the experiment, fungal samples were collected in April 2022. The swabs were done on DG18 and V8 media. After incubation at 20°C for 7 days, the samples were then examined under stereo and light microscopes. No other tests for microbial activity, such as bacteria or rot fungi, were carried out in the experiments.

3. Results

The graphic presentations of measurement data are drawn using running averages of 96 hours.

Boundary conditions

Figure 3a and Figure 3b show indoor and outdoor temperatures and RH, respectively.

System comparison

This section compares the humidity in the insulation systems without hydrophobization.

Figure 4 shows that generally high RH levels were found in the masonry/insulation interface. This was seen in all cellulose-based insulation systems (G7, X7 and G10), in the walls with hemp insulation (G5 and X2), and in the wall that was insulated with mineral wool and vapour barrier (G1). The RH levels of the walls with hemp or cellulose insulation had reductions during summer that were not seen in the wall with mineral wool. Overall, the RH levels of the bio-based insulation systems were similar, and they were not significantly different from the wall with traditional mineral wool and vapour barrier.

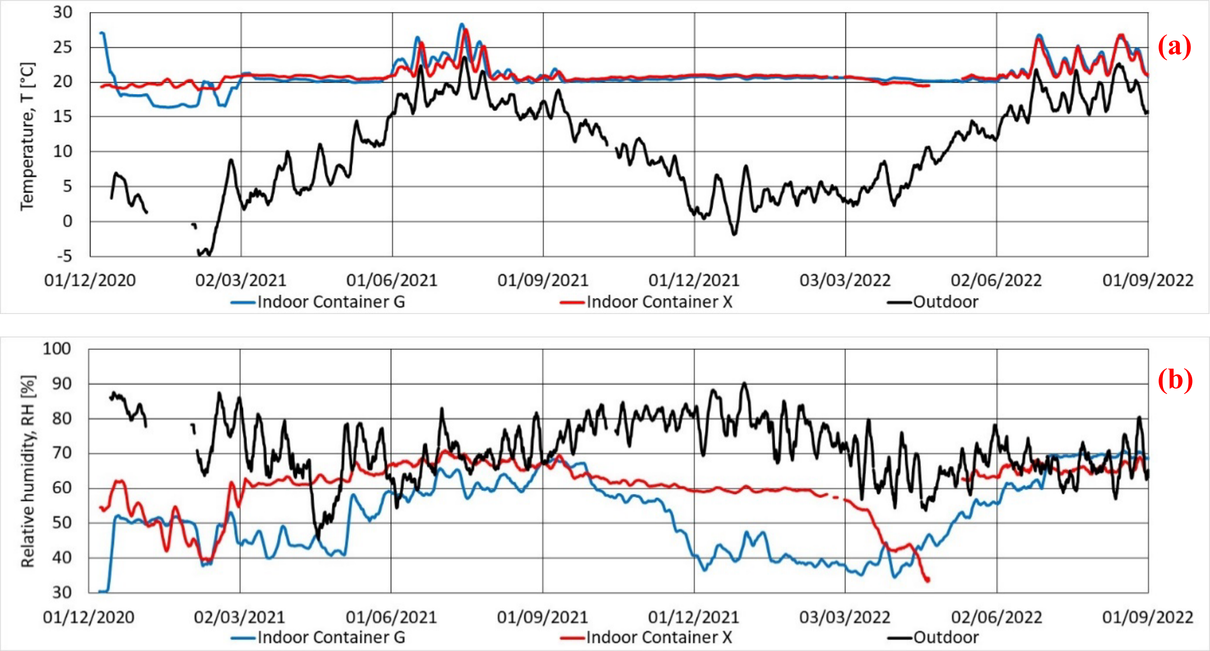


Figure 3. Indoor and outdoor boundary conditions. (a) Temperature and (b) RH.

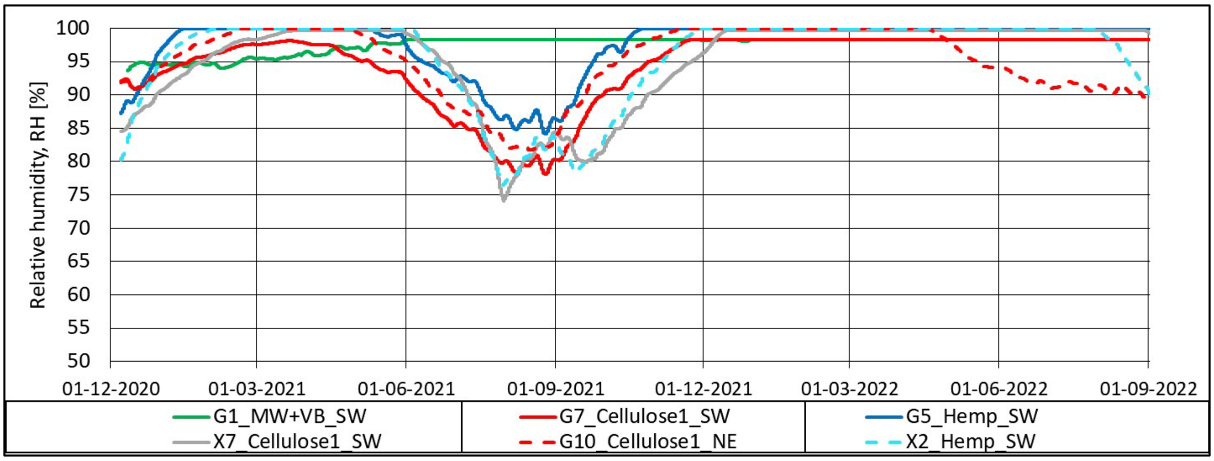


Figure 4. RH at point 3. Interface. SW: Southwest; NE: Northeast; VB: Vapour barrier.

Figure 5 shows RH levels for the embedded wooden wall plates, which were unacceptable throughout the measurement period in all three insulation systems. While the wall with mineral wool was at 100% RH for the entire measurement period, also the RH levels of the bio-based systems remained critically high throughout. Considerably drier conditions were found in reference walls X5 and G14 without interior insulation.

Effect of hydrophobization
Figure 6 shows that hydrophobization had a positive effect on the masonry/insulation interface. However, the effect is most noticeable in the summer when the RH levels are lower than those of un-hydrophobized walls. The effect of hydrophobization was larger in the southwest-facing walls than in the walls facing northeast. During winter, the RH levels of walls with and without hydrophobization were quite similar.

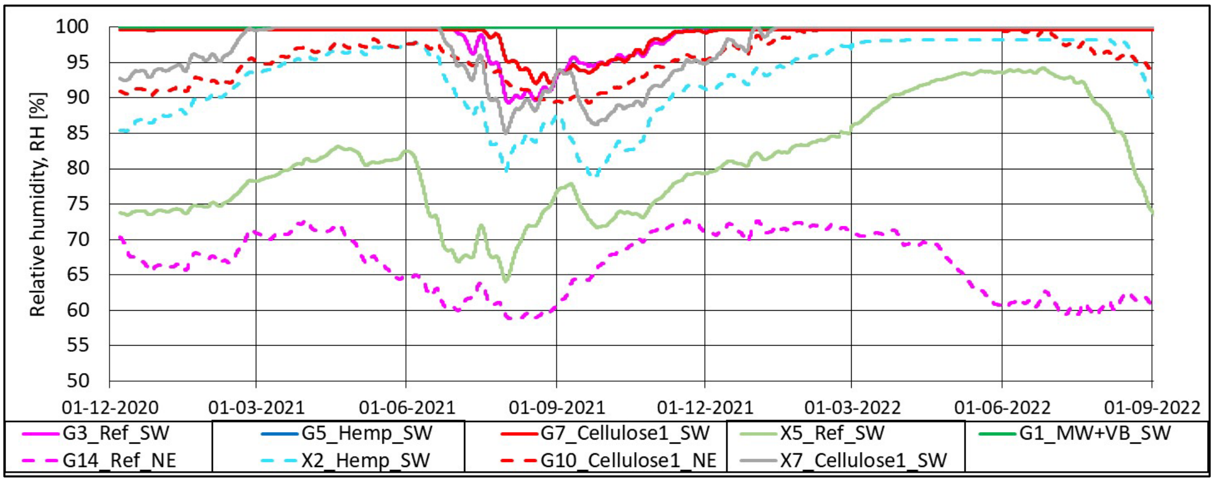


Figure 5. RH at point 5, wall plate. The curve for G5_Hemp_SW lies behind that for G1_MW+VB_SW. SW: Southwest; NE: Northeast; VB: Vapour barrier.

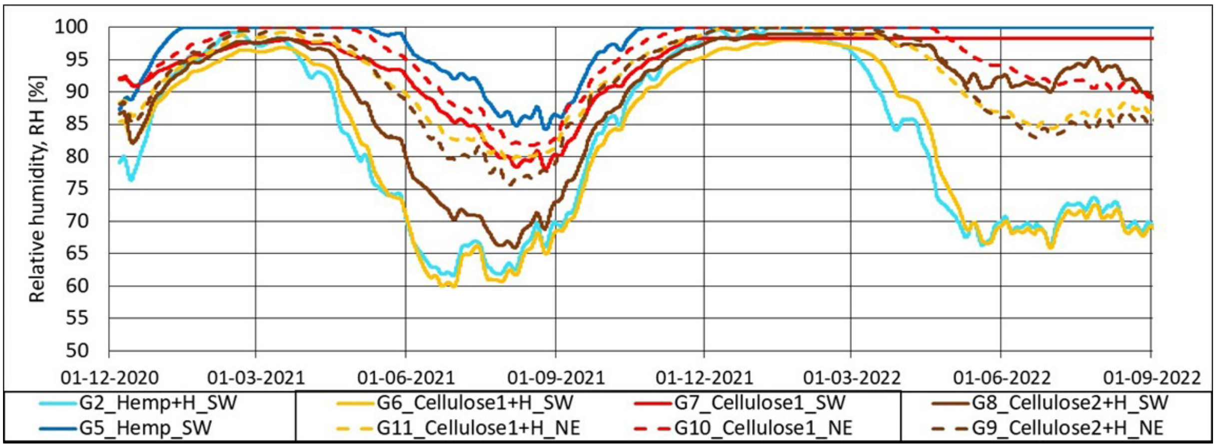


Figure 6. RH at point 3, the masonry/insulation interface. SW: Southwest; NE: Northeast; +H: Walls with hydrophobization.

Measurements for the wooden wall plate (Figure 7) showed a greater positive effect of hydrophobization than for the masonry/insulation interface. All hydrophobized walls had lower RH than un-hydrophobized walls, although the southwest-facing walls showed a stronger effect from the hydrophobization. Only one exception was the southwest-facing hydrophobized wall insulated with Cellulose2 (G8) which, for most of the measurement period, had RH levels comparable to the northeast-facing hydrophobized wall (G9).

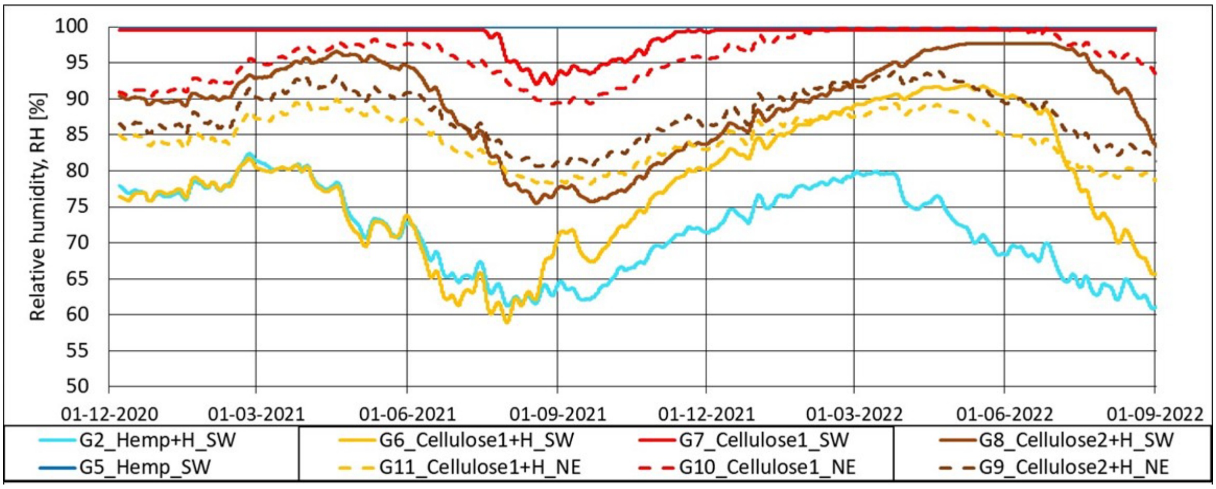


Figure 7. RH at point 5, the wall plate. SW: Southwest; NE: Northeast; +H: Walls with hydrophobization.

Fungal growth

Mycometer Surface tests have shown only a small amount of fungal biomass (mycelium and spores) in the interface between masonry and the interior insulation both when mineral wool or one of the two cellulose insulation types were used. However, in the case of hemp as interior insulation, a large amount of fungal biomass was observed in the masonry/insulation interface.

4. Discussion

Generally, high RH levels were observed in the masonry/insulation interface, for most of the measurement period. The hygrothermal conditions are quite similar on the tested bio-based insulation systems and even, the RH levels do not differ much from those observed in the traditional system with mineral wool and vapour barrier. A small reduction of the RH levels was seen in the bio-based insulation systems during some of the summer months, which is a pattern that was not seen in the traditional system, where RH levels remained around 100% throughout the summer. This may be a result of the diffusion-open properties of the bio-based insulation materials, and the omission of a vapour barrier, while in the traditional system, the vapour barrier limits inwards diffusion, which keeps up the high RH level during summer.

Critically high RH levels were measured in the wooden wall plate during most of the measurement period, no matter which kind of bio-based insulation material was used, and the situation was almost similar for the traditional system with mineral wool and vapour barrier. But again, small reductions were observed in the humidity level during summer in the diffusion open bio-based insulation systems.

Hydrophobization had a positive effect to reduce the moisture content in the exterior part of the masonry for all walls regardless of their orientation and type of bio-based insulation material used in the walls. However, it seems the hydrophobization had only a positive effect on the southwest-facing walls when it came to the RH levels in the interface between insulation and masonry and in the wooden elements, and slight reductions of the RH levels were seen in the wall plate of the northeast facing walls. Thus, it can be stated that the effect of hydrophobization was predominant in the direction of wind-driven rain and during summer. For the southwest-facing wall with a notable effect of hydrophobization, the effect was predominant in the interface during summer only, while the effect was negligible during winter. For the wooden elements, the hydrophobization had an effect to reduce the RH levels generally. Overall, despite the sometimes-positive effects of hydrophobization to reduce the RH levels, the treatment alone did not ensure non-critical RH levels, as they were still over 80%.

Compared to the results from previous experiments with other insulation systems that are not biobased [1] and [5], the overall results have not been significantly different: High RH-levels are seen in potentially critical locations in the wall systems at their wall plates, beam ends (which are not shown in this paper) and insulation/masonry interfaces.

Fungal growth

Only low amounts of fungal biomass were observed in the eight walls insulated with the loose fill cellulose insulation (Cellulose1 and Cellulose2), while high amounts of fungal biomass were observed in the walls that were insulated with hemp insulation after 1½ years. The reason for this difference is probably the type of flame retardant that was added to the insulation materials as the used products with boric acid are known to have a mould-preventing effect. Also, the Mycometer results indicated growth only in the walls insulated with hemp. For the other walls, the lack of fungal growth despite of high RH levels may be attributed to the effect of the mould-preventing additives.

5. Conclusions

The hygrothermal performance of 13 solid masonry walls has been assessed when they were insulated with one of three bio-based diffusion-open insulation systems. The walls were tested in an outdoor test field for 1 year and 9 months while investigating the risk of fungal growth in the walls. The test also investigated the effect of hydrophobization on the exterior masonry surface.

It can generally be concluded that high levels of relative humidity are found in bio-based insulation systems when the walls are not hydrophobized against wind-driven rain. However, hydrophobization seemed to somewhat reduce the humidity level in walls that face the dominating direction for wind-driven rain, and this is particularly the case during summer conditions. Otherwise, the effect of wall orientation seemed not to be a significant parameter if the walls were not hydrophobized.

On-site fungal tests found growth in the wall insulated with hemp, while no growth was found in the walls insulated with cellulose despite unacceptably high RH levels. The presence of fungal growth in the hemp insulation and the lack of growth in the cellulose were likely due to the use of a different type of flame retardant without boric acid. Also, from fungal cultivation on agar media, massive growth of several mould species was seen on the hemp samples, while only little fungal growth was observed on agar media from walls with cellulose insulations.

Overall, the result that humidity levels were unacceptably high in critical locations in the interior insulated wall systems, while it was still possible to prevent mould growth by using proper additives, is a result that resembles conclusions from previous experimental series with non-biobased insulation systems.

6. Acknowledgment

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