

Hygrothermal Evaluation of a Hybrid Façade System with Bio-Based Insulation

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Abstract. The shift towards a sustainable building industry requires increasing insulation thicknesses to lower operational energy, which in turn entails a higher impact of embodied energy. Consequently, bio-based materials are gaining interest, both in new projects and renovation strategies, e.g. as interior retrofit for existing masonry. Moreover, there is a growing trend in practice to reduce wall complexity and simplify layered constructions. This results in a new design approach, featuring an outer masonry leaf and an interior timber frame with bio-based insulation. This research examines the moisture behaviour of such hybrid façade systems based on the practice of BLAF Architects, a Belgian architecture office pioneering in sustainable construction. Over 30 of their wall systems were categorised based on their rainwater management concept. The risk of rainwater infiltration depends on the presence of capillary barriers like a cavity or a rainscreen. Therefore, further research into the hygrothermal behaviour of bio-based materials is required to ensure long-term durability. While their ability to buffer moisture is often seen as an advantage, it also results in a higher overall moisture content. To address this specific hygrothermal behaviour, 1D Heat, Air and Moisture (HAM) simulations in Delphin 6 are used to assess degradation in a trade-off with the simplification of the wall buildup. The simulations reveal that removing capillary barriers when using different types of hygroscopic insulation like cellulose and lime hemp affects degradation risks differently.

1. Introduction

Innovative construction solutions facilitate the transition to a sustainable building industry by efficiently managing building materials. While building codes primarily focus on operational energy, there is an increasing academic and societal debate about embodied energy, including aspects such as material production and end-of-life (1). The building industry accounts for nearly 37% of global CO₂ emissions, with 10% from traditional materials like concrete, glass and steel (2). In this regard, bio-based materials such as lime hemp offer great potential due to their low embodied energy and ability to sequester CO₂ during their growth through photosynthesis (3).

In this spirit, BLAF Architects proposes an alternative to the traditional brick cavity wall in **Figure 1**: a façade system comprising a self-bearing outer masonry leaf and interior timber frame with bio-based insulation. This wood framing is either load-bearing (new buildings) or self-bearing (retrofit). This system is commonly used as interior retrofit for existing masonry in



Belgium, but also offers major benefits for new buildings: eliminating thermal bridges from wall ties, reducing ceramic material use by 22-26 % per m², and allowing flexibility in the construction sequencing. The reduction can be enlarged by the use of perforated brick instead of solid masonry.

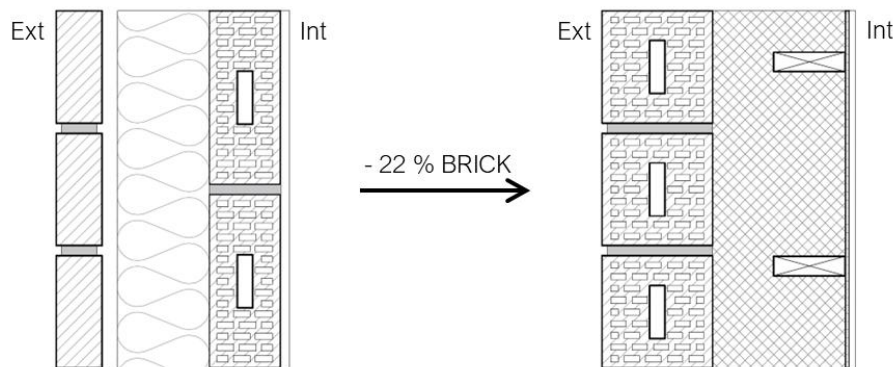


Figure 1. Wall buildup of the hybrid façade system (right) compared to the traditional cavity wall (left). The hybrid system consists of an outer self-bearing masonry leaf and interior timber frame.

However, this hybrid vapour-open double-shell wall highlights a concerning trend in wall systems with bio-based insulation. Moisture-sensitive bio-based materials are increasingly used, but capillary barriers like air cavities and rainscreens are being eliminated. This results in reliance on the watertightness of the outer masonry leaf, which is susceptible for rainwater infiltration due to joints, workmanship, and cracking (4,5). Such infiltrations can lead to high moisture levels, resulting in degradation or performance losses of the timber frame and bio-based materials (6,7).

This underscores the need for further research into the hygrothermal behaviour of hybrid façade systems. The goal of this study is twofold. First, to simplify the wall buildup by using less layers, less plastics and enhancing the circular reuse potential. And second, to ensure that the moisture buffering capacity of the bio-based insulation does not compromise the durability of the wall system. This study focuses on the moisture buffering, rainwater management and drying capacity of hybrid façade systems to evaluate potential degradation risks. A trade-off between simplification and durability of the wall system will be analysed. To begin, a typological categorisation of wall systems based on the infiltration risk is derived from the built practice of BLAF Architects. Next, hygrothermal 1D simulations in Delphin are used to assess degradation.

2. Methods

2.1. Typological categorisation of hybrid façade systems based on the infiltration risk

Starting from over 200 projects in the archives of BLAF Architects, more than 30 hybrid wall systems were identified that comply with the focus of this research, i.e. an outer masonry leaf and interior timber framing leaf. Subsequently, these walls were further categorised into 9 wall types V1 to V9, based on the infiltration risk of rainwater reaching the insulation material. A distinction can be made between walls with a rainscreen, a cavity, both, or neither. In some cases, unprotected insulation was also placed on the outside of the rainscreen. This categorisation can be visualized in a tree diagram based on 3 decision levels depending on the presence of capillary barriers as shown in **Figure 2**: is there a rainscreen, is there a cavity and is the insulation protected?

The higher a wall system is located in the tree diagram, the higher the infiltration risk based on the research of Van Linden (4). Two types of capillary barriers can be distinguished: a cavity and a rainscreen. In general, the presence of a cavity entails a lower infiltration risk than a rainscreen. The bigger the cavity, the smaller the chance that water droplets infiltrating the masonry can reach the inner material layers. Cavities of 20 mm or more have a high infiltration resistance. Rainscreens are often discontinuous, with overlapping and preferably taped joints. However, workmanship and the type of rainscreen strongly influence the watertightness. Therefore, the uncertainty on the infiltration resistance is larger and rainscreens are associated with a higher infiltration risk.

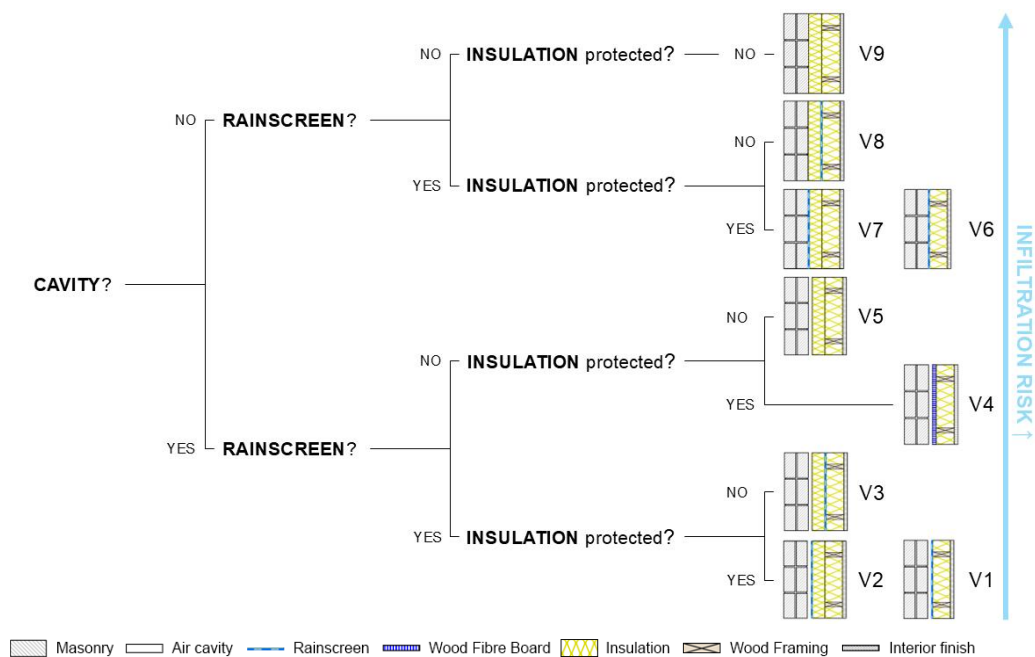


Figure 2. Tree diagram with classification of wall types V1 to V9 based on the capillary barriers.

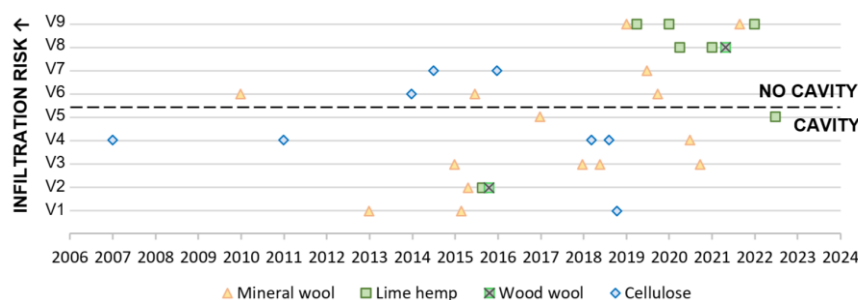


Figure 3. Evolution in time of the use of wall types V1 to V9 in the practice of BLAF Architects, based on 27 projects and 32 different wall builds. The datapoint represents the insulation type.

To gain insight into the evolving practice of BLAF Architects over time, all wall systems are represented in **Figure 3**. Again, higher datapoints indicate a higher infiltration risk. The colour and shape of each point denote the type of insulation used in the case. An increasing trend is visible, highlighting a shift towards the use of wall systems where insulation is less protected from

rainwater infiltration. This results in a higher reliance on the watertightness of the outer masonry leaf, a factor that was experimentally investigated in prior research (5). Early bio-based projects predominantly featured cellulose insulation, which was always protected by either a rainscreen or a cavity. These projects closely resemble traditional wood framing constructions with brick veneer. In contrast, more recent projects have increasingly incorporated lime hemp insulation, in combination with wall systems that exhibit a higher infiltration risk by eliminating the cavity.

Regarding the fact that bio-based (insulation) materials are moisture-sensitive, further investigation of the hygrothermal response of these wall systems is conducted by means of hygrothermal simulations.

2.2. Hygrothermal simulations – input and settings

Two series of simulations were conducted in Delphin 6. First, wall types V1 to V9 are simulated to estimate the hygrothermal impact of the capillary barriers. Walls V1 to V9 are modelled as walls with a U-value of $0.15 \text{ W/m}^2\text{.K}$. An overview of the materials is reported in **Figure 4**.

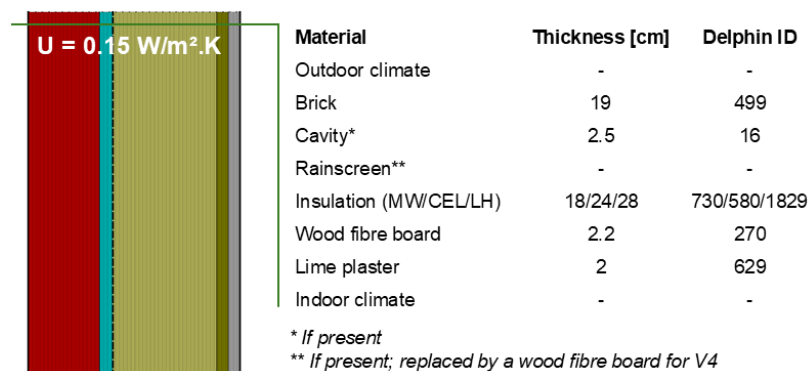


Figure 4. Wall geometry and information about the simulation model of types V1 to V9 in Delphin.

The selection of brick type ZK was found to be critical when evaluating wood degradation (8). The cavity is ventilated with 5 air changes per hour, which is considered as an average value for cavities behind a brick cladding (9). The rainscreen is modelled as an interface with a constant vapour diffusion ($s_d = 0.05 \text{ m}$), no liquid flux and no airflow. In V4, the rainscreen is substituted by a wood fibre board. This represents a standard wood framing construction with brick veneer cladding. Three types of insulation will be evaluated: mineral wool (MW), cellulose (CEL) and lime hemp (LH). The wood framing is not modelled in the 1D approach. For the outdoor climate, the moisture reference year (MRY) for Brussels of Vandemeulebroucke et al. is implemented for a south-west (SW) orientation (10). This is the most critical orientation in terms of moisture load on façades due to wind-driven rain (WDR) for Belgium. The rain exposure (RE) is set to 1, corresponding to a wall factor (W) of 0.4 according to EN ISO 15 927-3 (11). These settings simulate the impact of a high wind-driven rain load on a low-rise building in free field conditions for terrain category II and a flat topography. The corresponding dynamic indoor climate for Brussels of Vandemeulebroucke et al. is used (10). All coefficients for conduction, diffusion and radiation are based on the Delphin manual (12). A period of 15 years is simulated, to provide sufficient conditioning in order to reach equilibrium in the evaluation year.

Secondly, a one-factor-at-a-time method is used to assess the impact of six parameters on the simulation results for prototype V9, the most critical buildup. By changing the rain exposure (RE = 0.5, 1, 1.25, 2), different wall factors W are investigated ranging from 0.2 to 0.8. To study the

influence of the brick type, at least one brick from each cluster proposed by Vanderschelden et al. is simulated (bricks ZA, ZB, ZD, ZF, ZG, ZI, ZK, ZL) and the masonry thickness is varied (9, 14, 19 cm) (13). Although the SW orientation is critical, also north (N) and east (E) orientation are simulated. North is typically the coldest orientation inducing frost damage, east is representative for a monitoring campaign in future research. Measures to limit the moisture load on the façade are implemented by means of a watertight limewash (Delphin ID 150), realistic limewash (1% and 10% infiltration) and the use of hydrophobic brick ZQ (ID 534). Finally, infiltration rates of 0.6%, 1% and 10% found in literature were introduced to account for workmanship and cracks (4,14,15). This results in 22 variants for 3 insulation types (MW, CEL and LH), or 66 simulations. The reference case (REF) is a wall with brick ZK, RE = 1, 19 cm masonry and a SW orientation without infiltration.

2.3. Hygrothermal simulations – evaluation criteria

To assess different potential damage mechanisms, several evaluation criteria were considered. Based on the relative humidity of the insulation material, a first comparison of the hygrothermal behaviour of different insulation types and different levels of hygroscopicity can be made. For more quantitative insights, four damage indicators were used. Generally, a traffic light method will indicate whether a configuration is safe (green), more study is needed (orange), or unsafe (red). All results should be interpreted comparatively.

All damage criteria and their evaluation locations are shown in **Figure 5**.

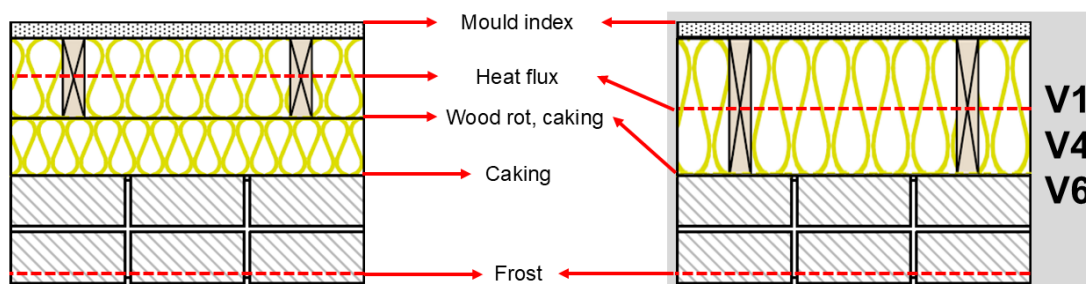


Figure 5. Evaluation criteria and their position in the simulation model for V1 to V9. For V1, V4 and V6, a different setup is used due to the presence of wood framing across the entire insulation.

First, mould growth on the inner surface is evaluated based on the improved empirical VTT model (16). A mould growth index M is calculated based on surface temperature and critical relative humidity. M ranges between 0 (no growth) and 6. The sensitivity class (very sensitive) and decline rate class (almost no decline) represent the most conservative assumptions.

Secondly, frost damage in the brick is evaluated based on the concept of critical freeze-thaw cycles (FTC_{crit}) at a critical depth of 5 mm (8,17). This evaluation is based on a critical saturation degree S_{crit} at which a material shows dilatation after exposure to freeze-thaw conditions.

Thirdly, degradation of the wood framing is evaluated at the outermost position of the wood using the dose-response model by Brischke and Rapp to evaluate wood rot (18,19). Based on the moisture content and temperature, daily doses d are calculated. To estimate degradation, decay ratings (DR) for brown rot, white and soft rot are used according to EN 252:2014 (20). The decay rating ranges from 0 (no attack) to 4 (failure) and is rescaled to a 4 year period, the timeline used in Brischke & Meyer-Veltrup (19). As no wood was modelled, the evaluation assumes that the capillary pressure at a given location in the insulation material is in equilibrium with the capillary pressure in the wood. Through the moisture retention curve of Spruce tangential (Delphin ID

713), the moisture content in the wood can be inferred. This wood species showed the best resemblance to experimental results (21).

Fourthly, the performance of the hygroscopic insulation material is evaluated. This is of great importance, as hygroscopic materials tend to have a higher average moisture content on a yearly basis, which results in lower thermal performance. To ensure equilibrium, no more moisture accumulation can occur, hence the increase in yearly average moisture content over a 5-year period should be lower than 1% according to EN 15026:2023 (22). The thermal performance is estimated based on the increase of the moisture-dependent heat flux (HF), in comparison to the heat flux in a simulation without rain load. The heat flux is calculated in the middle of the wood framing and only during the heating season. A 5% increase is a common threshold. For cellulose, caking occurs when the moisture content rises above 0.35 kg/kg mass percentage (m%). The maximum moisture content (MC) is calculated at the outermost location and after 10 cm.

3. Results and discussion

3.1. Hygrothermal simulations – wall types V1 to V9

In **Figure 6a**, the mean RH of the insulation materials is plotted in relation to the wind-driven rain (WDR) load for V9. The non-hygroscopic MW has a stronger fluctuating RH. With increasing hygroscopicity, the average RH increases respectively for CEL and LH, and variations flatten out. All simulations resulted in a mould index $M = 0$, so no mould risk occurred under the assumption of a controlled indoor climate and a high level of insulation. With regard to frost damage, as soon as the LH makes hydraulic contact with the brick (V6 – V9), the number of FTC in **Figure 6b** decreases significantly. The simulated LH with its fine pore system absorbs water from the brick, and this drying effect mitigates the frost damage risk in the brick. For CEL and MW, no big impact on the frost damage risk for the different wall types was observed.

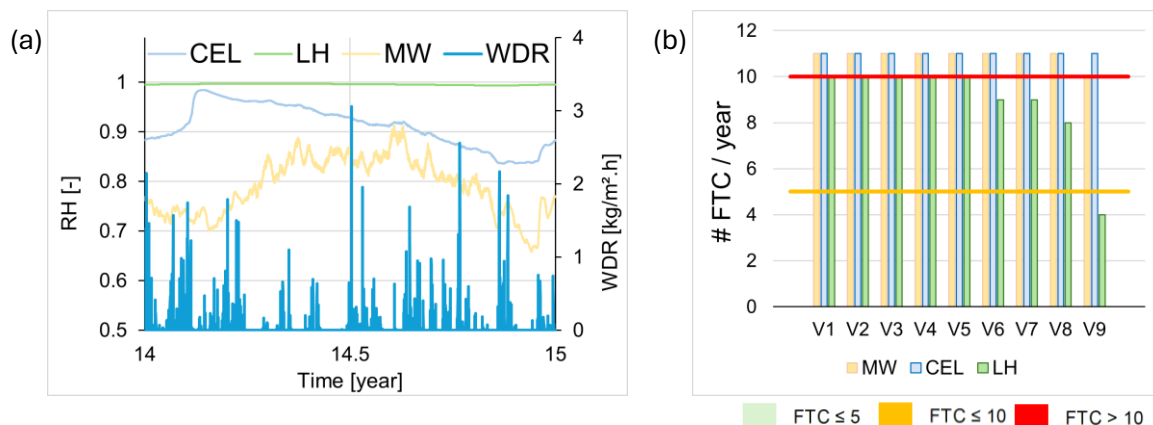


Figure 6. Simulation results: (a) average insulation RH of V9 for CEL, LH and MW (primary axis) and WDR load (secondary axis), (b) number of FTC for V1 to V9 during the evaluation year.

For wood rot, the decay rating (DR) for white/soft rot and brown rot is indicated in **Table 1**, calculated on a 4 year basis. To limit the risk for wood rot, the DR after 30 years should not surpass 1. Due to the conservative assumptions in these simulations, this is not the case. The simulations were executed with a severe climate (MRY), high rain exposure and the most critical orientation (SW). Note that this is not necessarily representative for every real-world scenario, so the results should be interpreted relatively. Generally, a higher risk occurs when there is no additional

insulation layer in front of the wood framing (V1, V4, V6). For all other wall types, only V8 and V9 result in risks for CEL. Hence, for CEL insulation at least one capillary barrier should be present to avoid contact with liquid water. For LH, the elimination of the cavity results in the highest risk increase. The difference between the wall types where liquid moisture transport is possible and those where it is not, is smaller. This can be explained by the hygroscopic behaviour of LH when the material is in contact with vapour. Capillary condensation occurs first in the smallest pores, and the simulated LH has a finer pore system than CEL. Thus, vapour passing through the rainscreen returns to liquid phase in the fine pores of the LH insulation. Therefore, the presence of a rainscreen in walls with LH insulation has less impact on the hygrothermal behaviour than the presence of a ventilated cavity. This results in a higher damage risk for V7-V9.

Table 1. Decay rating (DR) for wood rot of wall types V1 to V9 with CEL and LH on a 4-year basis. V1, V4 and V6 are indicated in grey as there is no insulation layer in front of the wood framing.

Wood framing		V1	V2	V3	V4	V5	V6	V7	V8	V9
CEL	White/soft rot	1.78	0	0	1.59	0	1.95	0	0.60	1.53
	Brown rot	3.38	0	0	3.25	0	3.49	0	1.97	3.17
LH	White/soft rot	1.14	0	0	1.31	0	1.36	1.66	1.69	2.44
	Brown rot	2.81	0	0	3.00	0	3.04	3.30	3.32	3.72
		DR < 0.5 "acceptable"			0.5 ≤ DR < 1 "slight attack"			DR > 1 "moderate to severe attack"		

Table 2. Heat flux increase (HF, in %) compared to a simulation without rain for wall types V1 to V9 with CEL and LH, and moisture content (MC, in m%) to evaluate caking at 2 locations (only for CEL). V1, V4 and V6 are indicated in grey as there is no insulation layer in front of the wood framing.

Insulation material		V1	V2	V3	V4	V5	V6	V7	V8	V9
HF increase		9%	8%	8%	8%	8%	11%	11%	14%	18%
CEL	Caking: MC outside	50%	50%	49%	45%	48%	61%	61%	123%	111%
	Caking: MC at 10 cm	13%	13%	14%	14%	14%	14%	14%	54%	94%
LH	HF increase	18%	18%	19%	21%	19%	23%	23%	30%	29%
		XX% HF↑ < 5% "acceptable"			XX% HF↑ > 5% "high increase"			XX% m% < 35% "no caking"		

The results of the heat flux increase in **Table 2** show an increasing trend depending on the degree of protection of the insulation. Both for CEL and LH, the biggest increase is observed for V8 and V9, due to the occurrence of liquid transport in respectively the outer or whole insulation layer. All scenarios have an increase in heat flux surpassing 5%. This can be explained by the hygroscopic nature of LH and CEL, which leads to higher moisture contents and thus less thermal performance over the heating season. **Table 2** also shows caking for all simulations at the outside of the insulation, but the first cell of the simulation grid can cause local effects. Therefore, an evaluation at a depth of 10 cm in the insulation is carried out. There, only V8 and V9 result in caking, due to the possibility of liquid transport.

3.2. Hygrothermal simulations – one-factor-at-a-time approach

In the previous paragraph, all evaluation criteria were discussed in detail. Now, to highlight the impact of parameters on the results for CEL and LH and to visualize trends, all results were discussed per parameter in Figure 7 and 8. In **Figure 7**, all criteria were normalised between 0 and 1. Simulation results are represented by a datapoint, trends by a connection line. In **Figure 8**, only the decay rating (DR) results for the 2 remaining parameters are discussed.

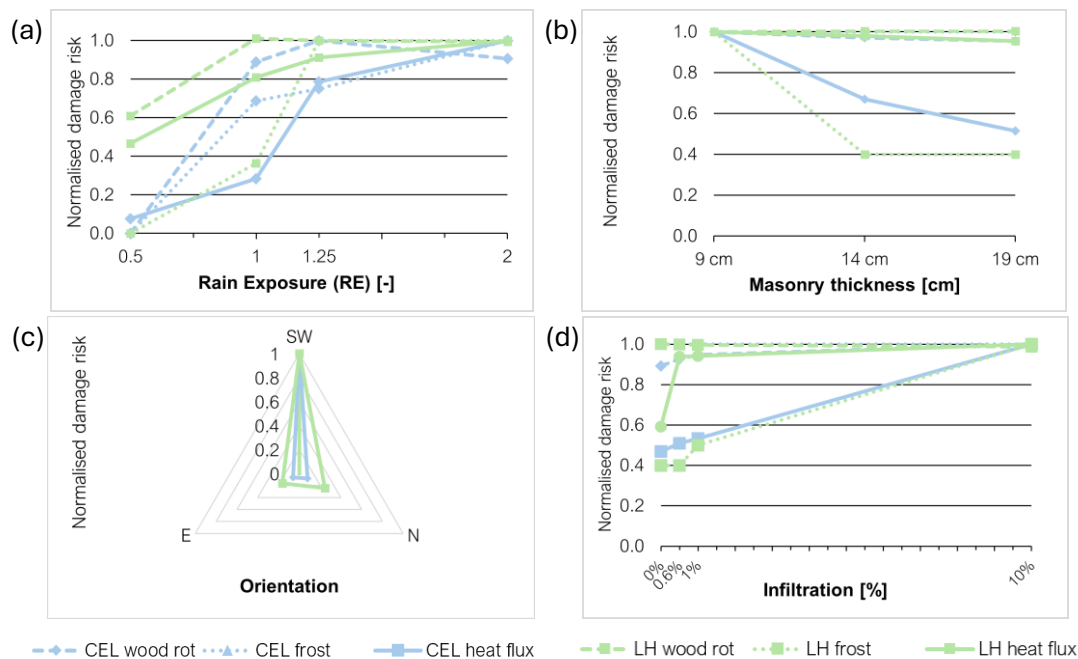


Figure 7. Simulation results of normalised damage risk per parameter: (a) rain exposure, (b) masonry thickness, (c) orientation, (d) infiltration. The legend applies to all Figures from 7a to 7d.

The expected damage risk in **Figure 7a** is proportional to the rain exposure (RE). The range between 0.5 and 1.25 clearly indicates that the choice of this value is crucial for whether or not damage might occur. The RE value in a simulation has a dominant impact and can be calculated according to EN ISO 15927-3:2009 (11). There is an apparent decrease in wood rot at RE = 2, but this is merely due to the calculation method of the dose-response model in combination with moisture content (MC) levels above 60 m%. When the MC is too high, the decay slows down.

The masonry thickness in **Figure 7b** has limited impact on frost damage and wood degradation. The highest impact is observed when going from 9 to 14 cm masonry. The thermal performance with CEL ameliorates significantly up to 19 cm masonry, with only half of the heat flux increase compared to 9 cm. This can be addressed to the limitation of liquid water transport.

The most critical orientation is evidently SW as can be seen in **Figure 7c**. N and E show no risk of frost or wood rot and the thermal performance is substantially better.

When considering infiltration in **Figure 7d**, the frost risk of walls with LH increases substantially. The biggest impact is visible on the thermal performance, with heat flux increases of 39% in CEL and 49% in LH during the heating season.

The brick type (ZA, ZB, ZD, ZF, ZG, ZK, ZL) barely had any influence on the simulation results with LH insulation regarding wood rot. This is reflected in the small standard deviation on the average results, represented by the error bars in **Figure 8a**. For brown rot in walls with LH insulation, the results are quasi identical for all 7 bricks. The modern brick type ZI is excluded

from the left graph but is visualised in the right graph, as it showed significantly lower degradation risks compared to all other bricks. Brick ZI is a modern brick type and is perhaps the most representative for new buildings, which is positive. Also, the thermal performance in walls with brick ZI is better due to a lower heat flux as there is less moisture storage.

Measures to limit the moisture load on the façade can mitigate almost every damage risk. However, workmanship will be of primordial importance, highlighted by **Figure 8b**. An infiltration of 1% through the limewash does not cause any problems. However, when 10% of the original rain load would infiltrate through the limewash, the risk of wood rot becomes even more problematic than if the protective layer were absent. There is again an apparent decrease for LH.



Figure 8. Simulation results of the decay rating on a 4-year period per parameter: (a) average values for the 7 simulated brick types except ZI (left) and results for brick type ZI (right), (b) results for limewash with different infiltration rates (%). Values are displayed for both CEL and LH insulation.

4. Conclusion

In this study, the hygrothermal behaviour of different wall types with bio-based interior insulation has been simulated and compared, based on the presence of capillary barriers. Hygrothermal simulations were carried out, both to investigate the impact of these capillary barriers as well as the impact of specific parameters and their most common values on the simulation results.

Rain exposure is the key parameter in simulations differentiating between acceptable and degradation-sensitive scenarios. To obtain representative results, it should be calculated case-specific, as this study relied on conservative assumptions. The wood framing in V1, V4 and V6 extends across the entire insulation layer and shows higher degradation risks on the outer side. A layer of insulation in front of the wood framing decreases the risk for wood rot significantly. However, this layer causes lower thermal performance when placed outside the rainscreen (V8).

For cellulose (CEL), a capillary barrier seems inevitable. Theoretically, the application of CEL insulation is possible if the masonry is watertight or impermeable through limewash or impregnation. However, prior experimental work indicated the former is not always the case (5), stressing the importance of the latter's performance. Workmanship will be crucial, as an infiltration of 10 % of the original rain load significantly deteriorates the simulation results.

For lime hemp (LH), higher average moisture contents are observed, especially in less protected wall types, which is also common practice. Thus, lower thermal performance and higher damage risks can be expected as a result of the higher degree of hygroscopicity of LH. A ventilated cavity proved to be the most impactful capillary barrier for LH. However, everything will depend on the realistic drying and wetting behaviour and potential damage mechanisms for LH under

such high moisture contents. This topic is still a vivid research area, and to the author's knowledge, no specific degradation criteria for LH have been established yet.

To conclude, there is a delicate balance in the trade-off between wall simplification and the predicted durability. It also depends on the choice of insulation material. For CEL, at least one capillary barrier should be present, regardless whether this is a cavity or a rainscreen. For LH, the cavity is the most crucial capillary barrier. Without capillary barriers, higher moisture contents can be expected due to moisture buffering. Monitoring, validation and further research should give more insight in the actual occurrence of the predicted degradation and performance losses.

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