Moisture Performance Requirements for Insulation in Exterior Wood-Frame Walls without a Vapour Barrier

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Abstract. An increased interest has been observed, especially among architects, in constructing the building envelope without using a vapour barrier membrane of polyethene (PE) foil. An increasing interest in biogenic building materials has also been expressed, as their use, besides storing embedded carbon, can reduce greenhouse gas emissions, replacing nonrenewable building components. Further, building envelope construction without a vapour barrier reduces expenses and the difficulty of the work process, especially around joints and penetrations. This study aims to determine the most important material properties of biogenic thermal insulation materials that influence the moisture-robustness of exterior wood-frame walls constructed without a vapour barrier. A literature study was performed to examine which material parameters have the most influence on the moisture conditions in an exterior wall without a vapour barrier. Hygrothermal simulations of lightweight exterior walls were performed to investigate the significance of variations in material properties (e.g., equilibrium moisture content and vapour diffusion resistance) and determine their necessary characteristics when used as thermal insulation material in an exterior wall without a vapour barrier in internal humidity class 3 (defined in EN ISO 13788). The moisture-robustness of the construction is assessed based on the risk of mould growth in the layer between the thermal insulation and wind barrier. The study suggests that the moisture capacity of the available common biogenic thermal insulation materials does not significantly affect the overall moisture performance of the wall. Simulations demonstrate that, for the thermal insulation layer in internal humidity class 3, at least one of the following requirements must be met to ensure moisture-robustness in exterior walls without a vapour barrier: (I) high diffusion resistance of the thermal insulation and (II) high moisture capacity of the thermal insulation material at relative humidity between 60% and 90%. Commercial biogenic thermal insulation materials on the market do not meet the latter requirement.

1. Introduction

This paper aims to investigate which parameters of biogenic thermal insulation materials in an exterior wood-frame wall without a vapour barrier have the greatest influence on moisture performance. Furthermore, the aim is to determine which material performance characteristics are important for biogenic thermal insulation materials in internal humidity class 3. This study also investigates which thermal insulation materials suit an exterior wood-frame wall without a traditional polyethene (PE) vapour barrier.

Studies [1, 2] have demonstrated that external wood-frame walls with hempcrete as the thermal insulation have a very good moisture performance; thus, this material was chosen for the study. The literature review [3, 4] suggests that the moisture capacity and capillary moisture transport properties of some thermal insulation materials e.g., cellulose insulation can help improve the overall moisture performance of exterior wood-frame walls without a vapour barrier. Latif et al. [2] concluded that the hygroscopic properties of the thermal insulation could help maintain hygrothermal stability in construction and reduce the risk of condensation.

As thermal insulation comprises the largest part of wall construction in terms of volume, it is relevant to investigate its moisture-buffering properties. Supported by [5], it is assessed that the moisture storage function and diffusion resistance have the greatest importance for moisture performance. Thus, this study focuses on the diffusion resistance and moisture capacity of biogenic thermal insulation. The study includes modifications of the sorption curve of the thermal insulation material to predict how the moisture performance can be improved. The study predicts the moisture-robustness of the exterior wall based on the risk of mould growth.

2. Method and materials

Figure 1 illustrates the investigated structure that was used throughout the study. The study focused on the properties of the thermal insulation layer, which was investigated using different materials or altered properties, such as the moisture storage function. The structure is a common exterior wood-frame wall used in Denmark with a thermal transmittance of approximately 0.15 W/m^2K when installed with mineral wool. A traditional wood-frame wall is typically constructed with a vapour barrier of a 0.2 mm PE-membrane; however, this study focuses on structures with biogenic thermal insulation material without a vapour barrier.

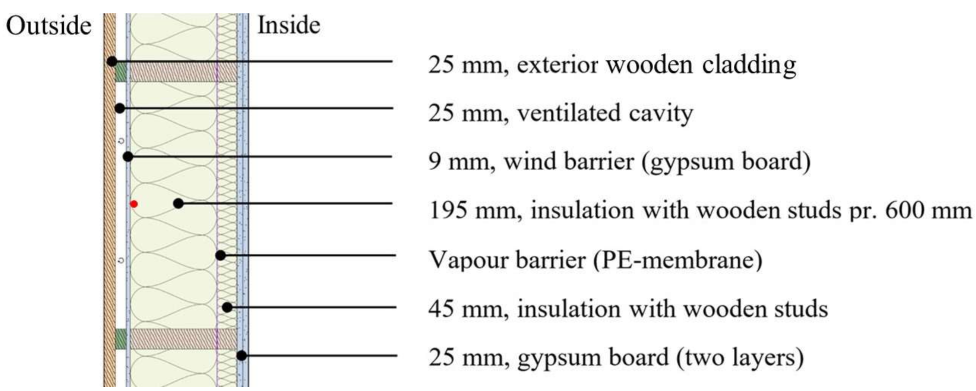

Figure 1. Horizontal section of a typical Danish exterior wood-frame wall. The red dot is the point of investigation located in the interface between the thermal insulation material and wind barrier.

Two reference walls were used, one with thermal insulation of mineral wool and one with cellulose, both with a vapour barrier with s_d = 1 m [3] (Regardless the thickness of the vapor barrier, the thickness of 1 mm is default in WUFI calculations). However, a vapour barrier in Denmark is normally considered to have an s_d > 10 m [6]. These two structures were used as the benchmark for walls with biogenic thermal insulation without a vapour barrier, as they should perform equally or better than typical wood-frame walls. The thickness of the thermal insulation layer was kept the same as in the reference construction for all parameter variations.

2.1. Material properties

Table 1 presents the properties of the materials, including a fictitious thermal insulation material, which is a copy of the cellulose insulation but with a modified moisture storage function. The diffusion resistance for all materials was kept constant, i.e., independent of the moisture content. Figure 2 depicts the moisture storage functions for various thermal insulation materials used in the study, including the fictitious material. The moisture storage function of the latter material is characterised by an increase in moisture content between 60% and 90% relative humidity (RH), thus the moisture content at 60% RH is 18.7 kg/m^3, at 70% RH is 280 kg/m^3 and at 90% RH is 380 kg/m^3. The moisture capacity of insulation is mentioned as a significant parameter [3, 4]; therefore, a new sorption curve was developed to investigate the influence of a high moisture capacity of the insulation. The curve of the fictitious material was defined based on an iterative calculation process, increasing the moisture content, to reach a moisture level just below the risk of mould growth.

Table 1. Properties of materials.

Material	Density [kg/m³]	Porosity [m³/m³]	Specific heat capacity [J/kg K]	Thermal conductivity [W/m K]	Diffusion resistance, μ [-]
Wooden cladding	420	0.75	1600	0.13	50
Wind barrier, gypsum board	1153	0.52	1200	0.32	16
Mineral wool	32.5	0.95	840	0.032	1
Cellulose insulation	50	0.95	2110	0.037	1.8
Wood fibre insulation, high density	260	0,83	1400	0.048	1.8
Wood fibre insulation, low density	140	0,91	1400	0.039	3
Hempcrete	280	0.83	1400	0.081	4.09
Fictitious insulation material	50	0.95	2110	0.037	1.8
Vapour barrier	130	0.001	2300	2.3	1000
Gypsum board	850	0.65	850	0.20	8.3

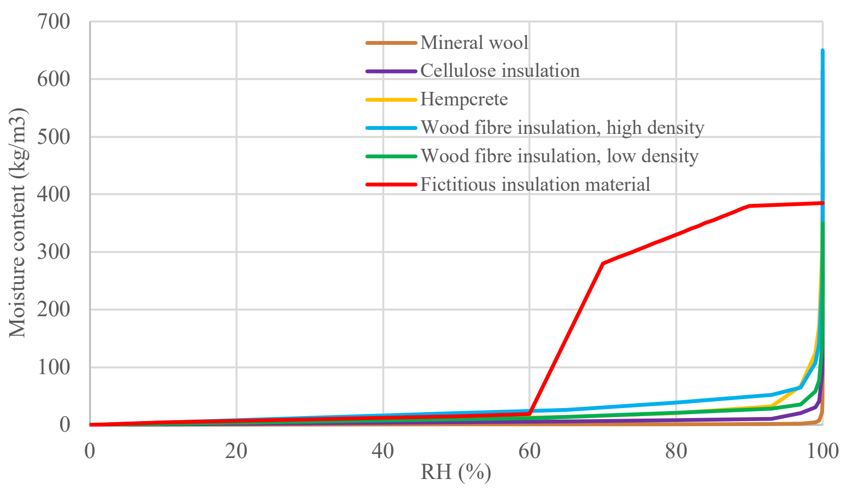

Figure 2. Moisture storage functions used in simulations.

2.2. Simulations and boundary conditions

The parametric study was conducted using the one-dimensional hygrothermal simulation tool, WUFI-Pro [7]. The results for temperature and RH were taken at the interface between the wind barrier and insulation (Figure 1). The simulations were conducted until periodic stability was achieved, and the results display the last simulated year. First, the commercial thermal insulation materials were investigated. Second, the fictitious thermal insulation material was created with an altered moisture storage function. The exterior climate was that for Lund, Sweden, considered representative for Denmark as currently such data are not available for Denmark. The interior climate was set to internal humidity class 3 [8] with an average indoor temperature of 20°C. The wall was oriented towards the north, the most critical orientation for ventilated exterior walls in Denmark due to less solar radiation. The surface coefficient for the wall was set as the default value; however, the exterior facade was assumed untreated (s_d = 0 m), and silicate paint was applied inside (s_d = 0.01 m).

2.3. *Mould risk assessment*

The comparison of the configurations of the exterior walls was first based on the RHT index [9]. Then, an assessment was made, applying the Lowest Isopleth for Mould (LIM) model [10].

2.3.1. RHT index. The cumulative RHT index was calculated according to Equation (1) for each simulation time step. A higher RHT index indicates a greater risk of mould:

$$\text{Cumulative } RHT = \sum (RH - RH_X)\times(T - T_X);\ RH > RH_X\,[\%] \text{ and } T > T_X\,[°\text{C}], \qquad (1)$$

where RH_x and T_x represent the limit values for the RH and temperature, respectively. In addition, RH_x was set to 75% for biogenic material [6], and T_x was set to 0°C, as several mould models neglect mould growth below 0°C [10, 11].

2.3.2. Isopleth model (*LIM*). The risk of mould growth was assessed in more detail based on the isopleth models [10] for biogenic materials. The daily average was used to simplify data processing. The threshold for mould growth was set to the eight-day curve. The eight-day curve defines a limit for mould growth on organic surfaces in RH (%) as a function of temperature. Subsequently, if the number of days in a row exceeding the threshold for mould growth was less than eight, the construction was considered moisture safe. If there were eight or more days with conditions favourable for mould growth, it was assumed that there was a risk of mould growth. This evaluation method is approximate because a 24-hour average of the hourly data was used. The eight-day threshold was used to evaluate the risk of mould growth, as the 16-day threshold was considered too conservative. Using the 16-day model to evaluate the risk of mould growth demonstrated growth in the reference construction, which is generally not expected.

3. Results

A summary of the results is presented in Figure 3. Horizontal bars that exceed the dashed line indicate that the RHT index is higher than in the reference construction. The reference construction with mineral wool insulation had an RHT index of 14,636, and that with cellulose insulation had an RHT index of 13,802.

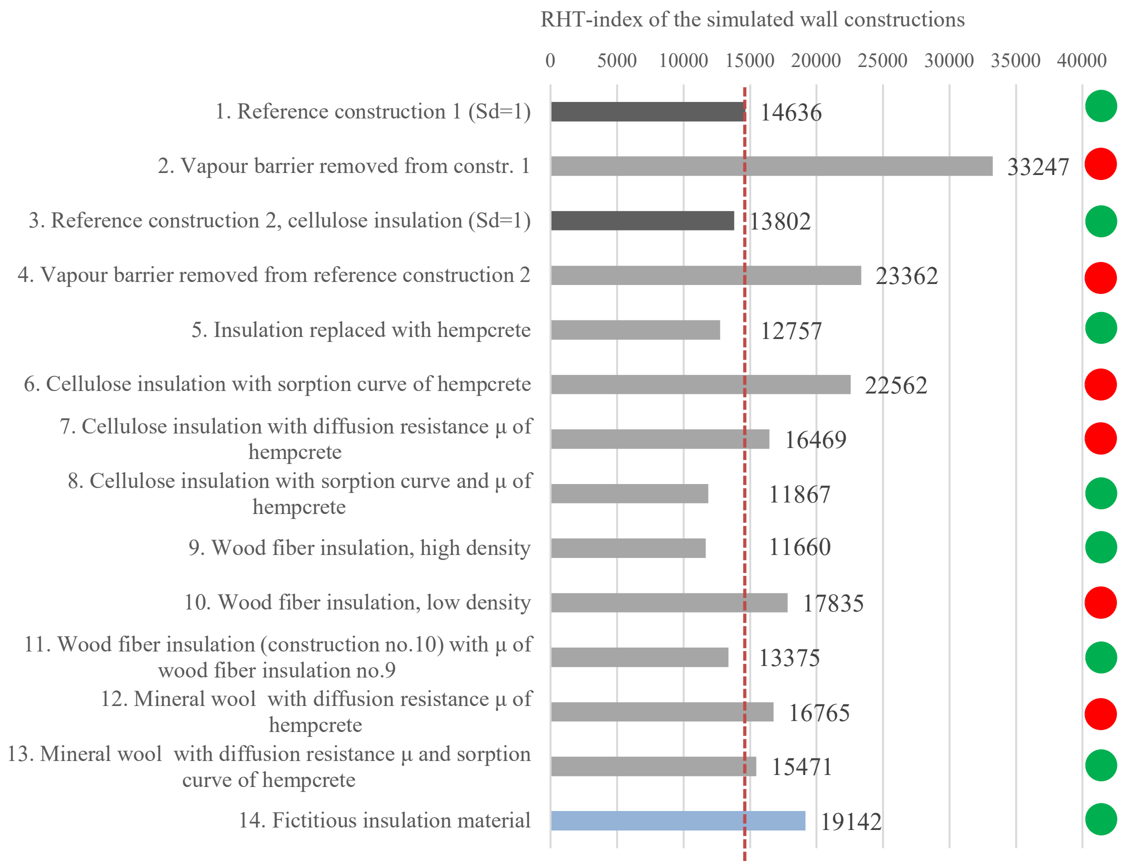

Figure 3. Summary of results; bars represent the RHT index of simulated construction. Horizontal bars exceeding the dashed line indicate that the RHT index was higher than that for the reference construction (#1) in Figure 1. Constructions 2, 4, and 5–14 (blue and light grey bars) are without a vapour barrier. In Constructions 5 to 14, modifications are only performed on the thermal insulation layer. Red dot indicates risk of mould growth for the specific construction according to Isopleth model (LIM). Green dot indicates no risk of mould growth according to LIM.

3.1. Reference construction

Removing the vapour barrier from the two reference constructions results in the risk of mould growth. The construction with cellulose thermal insulation has a lower risk of mould growth than that with mineral wool. Cellulose has an RHT index value of 10,000 lower than calculated for mineral wool used as thermal insulation. The results of the RHT index are provided in Figure 3. Reference constructions are denoted as Constructions 2 and 4. Constructions 1 and 3 are the reference structures with the vapour barrier.

3.2. Hempcrete

The construction without a vapour barrier and the thermal insulation of hempcrete reveal that the RHT index (12,757) is lower than the reference construction. Figure 4 depicts the annual progression of the RH, temperature, and associated limit value for the risk of mould growth according to LIM in the reference construction and the construction with the thermal insulation of hempcrete. The RH in the construction with hempcrete is minimal and stable compared with the reference construction.

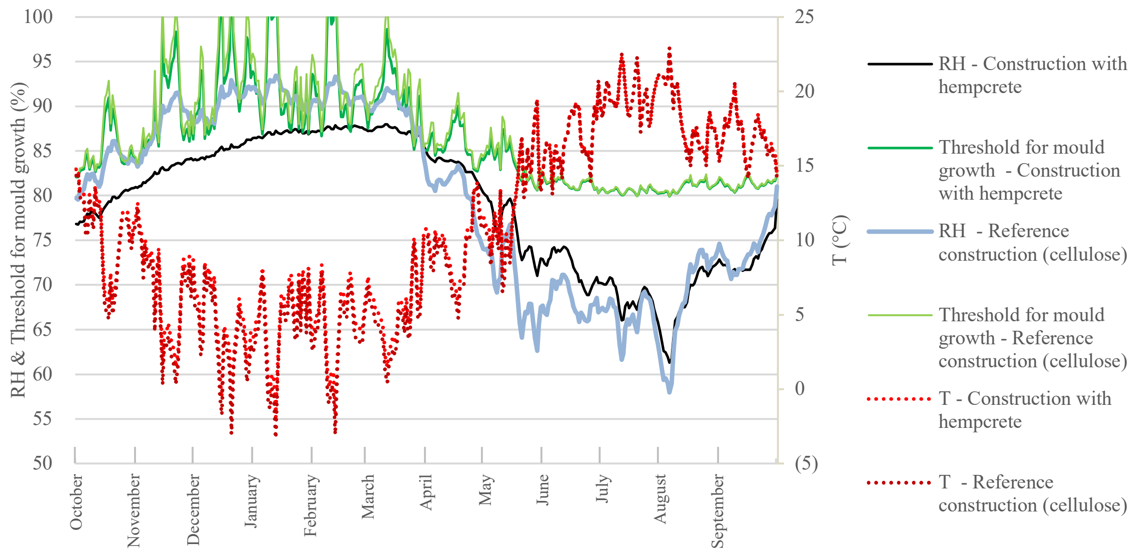

Figure 4. Relative humidity, temperature, and risk of mould growth behind the wind barrier in the construction with thermal insulation of hempcrete (Construction 5 in Figure 3) compared to the reference construction with cellulose thermal insulation (Construction 3 in Figure 3), presented as an annual variation. According to the LIM model, there is no mould risk in either of the two constructions.

Properties of hempcrete that contribute to the moisture-safe results were objects for parameter variation. Therefore, Construction 4 in Figure 3 was used for the evaluations, changing one parameter for the thermal insulation at a time. Parameters from hempcrete were initially used. Based on the literature review, the moisture storage function and diffusion resistance of the thermal insulation layer were examined. All variations (Constructions 6 to 8) are illustrated in Figure 3. The diffusion resistance was observed to have the most influence on the risk of mould growth.

3.3. Wood fibre

Figure 5 presents the results for the construction with wood fibre thermal insulation with a low (140 kg/m^3) and high density (260 kg/m^3). The construction with wood fibre insulation with a higher density achieves much better results in terms of moisture safety due to the higher diffusion resistance of the thermal insulation.

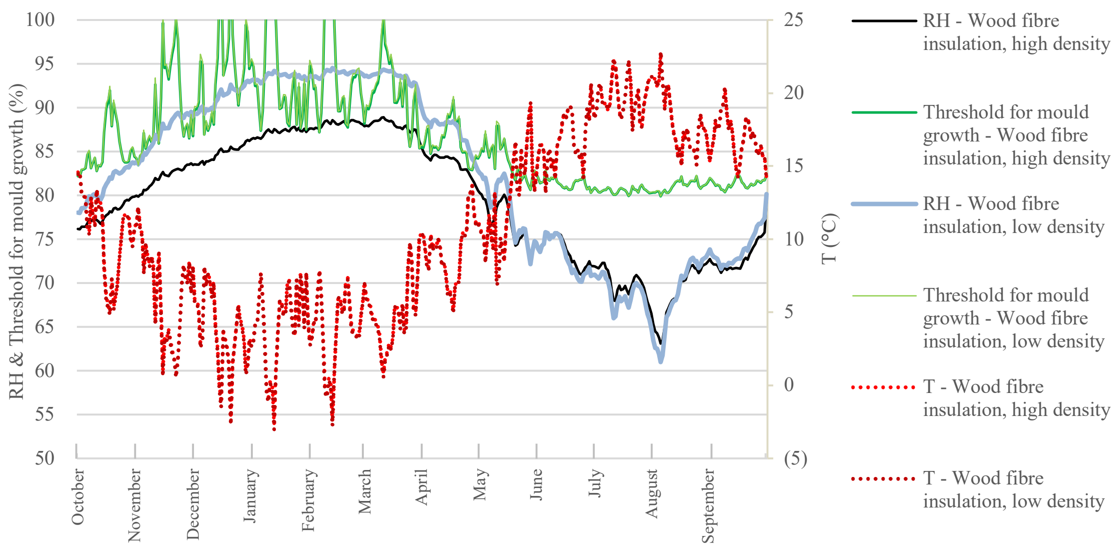

Figure 5. Relative humidity, temperature, and risk of mould growth behind the wind barrier in the construction with wood-fibre thermal insulation with a high density (Construction 9 in Figure 3) compared to a low density (Construction 10 in Figure 3) displayed as an annual variation. There is no risk of mould growth in the construction with the thermal insulation of high-density wood fibre. However, according to the LIM model, there is a risk of mould growth in the construction with the thermal insulation of low-density wood fibre.

3.4. Modified mineral wool

The RHT index for the construction with the thermal insulation of mineral wool with assigned diffusion resistance as for hempcrete is provided for Construction 12 in Figure 3. In Construction 13, the moisture storage function of hempcrete was also assigned (Figure 3). A significant influence of the change in parameters is observed for the overall moisture performance compared to Construction 2, which is the reference construction with thermal insulation of mineral wool and no vapour barrier.

3.5. Test of moisture storage function – fictitious material

The results indicate that the diffusion resistance and not the moisture capacity has the most effect on the moisture performance of the biogenic thermal insulation material. However, the moisture storage functions derived from the material library in WUFI Pro tend to significantly increase moisture capacity for high RH values (95% to 100% RH). The moisture-safe constructions usually do not exceed 95% RH; thus, the increase in moisture capacity at 95% to 100% RH can be neglected. However, a moisture storage function with a strong increase of approximately 60% to 90% RH might influence the overall moisture performance. Such a curve for a fictitious insulation material is depicted in Figure 2. Even though the calculated RHT index is higher than for the reference construction, the construction with the thermal insulation using the fictitious material (Construction 14 in Figure 3) indicates no risk of mould growth (according to LIM model). A higher moisture capacity (between 60 and 90% RH) resulted in better moisture performance.

4. Discussion

The study suggests that diffusion resistance could be a decisive parameter for thermal insulation material in an exterior wall without a vapour barrier in commercially available thermal insulation materials. Thermal insulation material with high enough diffusion resistance acts as a vapour barrier.

In reference studies, hygrothermal simulations [4] and field studies [2] demonstrated a good moisture performance for biogenic materials, and both studies assumed this was due to the high moisture capacity.

However, the literature studies do not consider the diffusion resistance of thermal insulation. Other studies have supported and suggested that the moisture capacity of the thermal insulation material has a modest effect on the moisture performance of the construction [12, 13].

If possible, modifying the sorption curve (moisture storage function) of the thermal insulation material is another method of achieving an exterior wall without a vapour barrier without the risk of mould growth. In this case, the thermal insulation material requires a high moisture capacity (over approximately 300 kg/m^3) between an RH of 70% to 90%. However, thermal materials with such a moisture storage function have not been available on the market but might be able to be developed in the future. It can possibly be achieved by incorporating various adsorbents, modified materials, or by combining different materials.

The study reveals that hempcrete and high-density wood fibre thermal insulation types have good moisture performance due to a high diffusion resistance. Therefore, it is likely that the vapour barrier can be omitted in such constructions. However, simulations conducted in internal humidity class 3 demonstrated that, for the reference construction with cellulose thermal insulation, the overall moisture performance was better than in the reference construction with mineral wool as the thermal insulation, but not enough to omit the vapour barrier. However, a vapour barrier with a diffusion resistance lower than a PE-membrane might be used to prevent the risk of mould growth in internal humidity class 3. Such a vapour barrier can be a more sustainable alternative e.g., made of paper, to eliminate the need for the plastic material. It is noted that the diffusion resistance was considered as a constant in the study. Its variation with RH, or water content, is however of interest to clarify.

It is important to acknowledge, that thermal conductivity is dependent on the moisture content. In the case of the examined exterior walls without a vapor barrier, the thermal performance can significantly decrease with an increased moisture level in the insulation.

Air tightness in the walls without vapour barrier must be ensured by other materials than the PE-membrane, as any leaks will increase moisture transport into the construction. The present study involved the simulation of the construction using internal gypsum cladding and assumed, that an air-tight connection between the gypsum boards (such as tape) was established.

5. Conclusion

This study investigated the parameters of biogenic thermal insulation materials in an exterior wood-frame wall without a PE-membrane as a vapour barrier, which had the most influence on the construction moisture performance. Furthermore, the study provides parameter characteristics for biogenic thermal insulating materials in exterior wood-frame walls without a vapour barrier that would perform without the risk of mould growth in internal humidity class 3, defined in EN ISO 13788 [8].

The paper investigated the parameters of diffusion resistance and moisture capacity as options for the parameters with the most influence on the moisture performance of exterior wood-frame walls without a vapour barrier. The diffusion resistance is the parameter with the most influence on moisture performance for a biogenic thermal insulation material in an exterior wall without a vapour barrier.

The study investigated a few biogenic thermal insulation materials on the market. The study found that when using hempcrete or high-density wood fibre as the thermal insulation material, it is likely that the vapour barrier can be omitted. However, a vapour barrier will lower the risk of mould growth.

A thermal insulation material with a high moisture capacity (over approximately 300 kg/m^3) between 70% and 90% RH was suitable for use in an exterior wall without a vapour barrier, providing no risk of mould growth. However, a thermal insulation material with such a moisture storage function was unavailable on the market.

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