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# Energy and moisture in historic masonry walls retrofitted with hemp-lime

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**Abstract.** Thermally insulating historic buildings is imperative in order to reduce energy demands of the existing building stock. Therefore an insulation material is needed that improves energy efficiency while being compatible with the existing structure from a hygrothermal, aesthetic and cultural heritage perspective. Hemp-lime is a building material that consists of on a combination of hemp shiv, the woody core part of the hemp stem, and building limes. The aim of this study was to determine if hemp-lime could be a feasible option for thermally insulating historic masonry walls in Sweden. The objectives were to measure energy performance of full-scale masonry façades insulated with hemp-lime and to monitor moisture levels inside the masonry walls. Three small single leaf masonry façades were constructed. One façade was uninsulated, the other had internal hemp-lime insulation and a third had external hemp-lime insulation. Energy use for space heating as well as temperature and relative humidity in the walls and rooms were monitored. Results show that thermally insulating historic masonry walls with hemp-lime can lead to an improvement in energy performance of 44-53 % compared to uninsulated single-leaf masonry. However, moisture levels were higher in the masonry façades that were insulated with hemp-lime.

## 1. Introduction

Thermally insulating existing buildings is imperative in order to reduce energy demands of the existing building stock. Thermal insulation that is used for retrofitting today is often highly insulating but also very diffusion-tight. Historic buildings are commonly built with materials that are diffusion open and allow moisture to move through the material. When insulating historic buildings with modern diffusion-tight insulation materials such as mineral wool and EPS this changes the hygrothermal properties of the wall completely. Therefore modern energy retrofits may not be appropriate for historic buildings and could even cause damage which can result in loss of cultural heritage values [1]. However, energy retrofits of historic buildings can nowadays also be viewed as a protection tool, as improving energy performance ensures that the building meets modern energy requirements, it promotes better use of the building and thereby extends its life-span [2].

Thermally insulating historical masonry walls can be challenging. External insulation tends to change the entire appearance of the building, with lost cultural and heritage values as a consequence [1]. As the internal surface often is plastered with lime mortar it is easier to add internal insulation without causing a great change in appearance, if the insulation layer can be part of a new plaster. Hence, internal insulation is preferred from a heritage point of view. However, when applying internal insulation on a masonry façade this can change the hygrothermal properties of the walls to such an extent that it leads to moisture problems such as interstitial condensation, moisture damage and frost-



scaling [3]–[6]. And if the internal insulation layer is not compatible with a new lime plaster there is another risk at changing the aesthetic expression and loosing heritage values. The essence is that an insulation material is needed that improves energy efficiency while being both compatible with the masonry from a hygrothermal perspective and compatible with lime plaster from an aesthetic and cultural heritage perspective.

Over the past decades a diffusion open building material called hemp-lime has been used in France, the United Kingdom [7] and elsewhere in Europe in new buildings, but also when renovating historic buildings [7]–[9]. Hemp-lime is a building material based on a combination of hemp shiv (the woody core part of the hemp stem) and building lime. In Sweden it is still a relatively unknown building material. As hemp-lime is a thermally insulating and diffusion open material it has potential to work very well as a material for retrofitting historic buildings. And as hemp-lime can be used as part of the plaster or render together with covering lime mortar it is interesting to use wherever there is a need for re-rendering or re-plastering.

Internal insulation usually leads to lower temperatures at the ends of timber beams in masonry walls [5], this can lead to an increase in moisture content and ultimately to moisture damage such as microbial growth. Internal wall insulation can also lead to frost-scaling of the external masonry. According to Vereecken [5] the internal wall insulation hinders an inward drying of the masonry wall and as the indoor heat does not reach the masonry wall to the same extent, the lower temperature of the masonry wall leads to a decreased drying potential of the masonry towards the outdoor climate. This can lead to an increase in moisture content of the masonry wall. High moisture content in the masonry in combination with a cold (Swedish) climate can lead to an increased risk for frost damage. Using a diffusion open material such as hemp-lime for enhancing thermal resistance of historic masonry could improve energy performance of the building while preventing moisture damage and preserving heritage values of the facades.

This paper explores the use of hemp-lime as an insulation material for retrofitting historic masonry walls. The aim of this study was to determine if hemp-lime could be a feasible option for thermally insulating historic masonry walls in Sweden. The objectives were to measure energy performance of full-scale masonry façades insulated with hemp-lime, for an external insulation as well as internal insulation scenario, and to measure changes in moisture levels inside the walls.

## 2. Materials and Methods

Three small masonry façades were constructed at the campus of Lund Faculty of Engineering. Here a lab building was available for testing energy performance of façade sections. The three façade sections were constructed using bricks produced by Hellingsø Tegelvaerk A/S (brick type 2.2.07 Swedish), that were reminiscent of historical masonry. Behind each façade section there was a small room (1.12×1.04×2.08 m) that was thermally insulated towards the surrounding lab building in order to reduce any heat gains and losses from these rooms to the lab building. Energy losses and gains through the internal walls were kept as low as possible by keeping the temperature in the three rooms as well as in the surrounding building at approximately 20°C. All façade sections were south-facing. The three small rooms behind the façade sections were each heated separately using a small frost guard 200 W (Anslut®). Power used for space heating (W) was monitored continuously using INTABs WiSensys® Wireless Sensing System. Monitoring and measuring of power for space heating was only performed throughout the heating season. Monitoring of space heating started once all measurement equipment was in place on the 10th of October 2017. It continued until 26 May 2018 after which no more space heating was required. Unfortunately no cooling was available which meant that temperatures, especially during the summer months, could not be completely controlled.

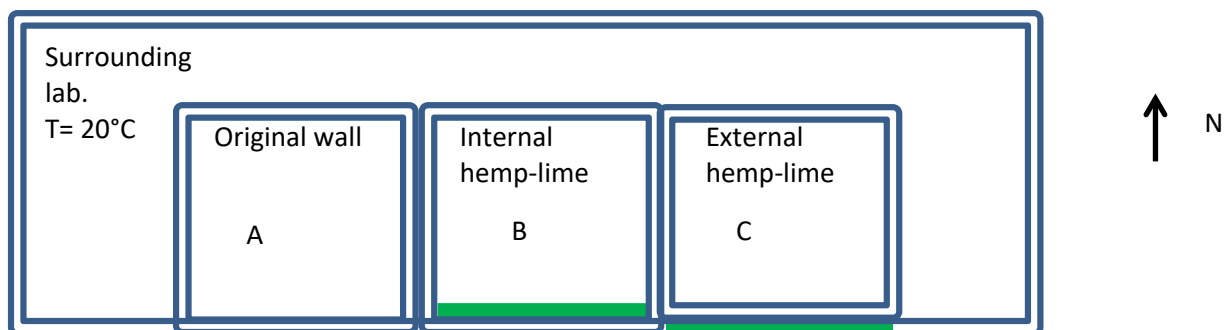


**Figure 1.** The use of hemp-lime for internal insulation is illustrated as it is used on an old brick wall in a Swedish church in the need for re-plastering. Here part of the lime plaster was changed to a hemp-lime layer, covered with a thin layer of lime plaster.

Temperatures and relative humidity inside the test rooms, the surrounding building and the outdoor temperature were measured every 15 minutes using HOBO ONSET MX2301 loggers. Relative humidity and temperature inside the test rooms was measured using TESTO data loggers. In order to not miss any values, measurements of the power used to heat the rooms were made every second. These values per second (in Watt) were then converted into hourly values (kWh). These hourly values were then converted into daily mean values for energy use (kWh/day).

As room A used a PID-controller (situated outside of the room) some energy was used by this device. When space heating was ongoing a total of 222 W was measured (compared to 217 W for the rooms without PID-controller). When no energy was used for space heating the values that were measured were 2 W (compared to 0W for the rooms without PID-controller). Therefore a small compensation had to be made to exclude the energy that was used by the PID-controller from the energy use of the room. This compensation was calculated as follows;

$$P_{\text{compensated}} = P - \left( \frac{P}{222} \cdot (222 - 217) \right) + \left( \frac{1-P}{222} \cdot (2 - 0) \right) \quad (1)$$



**Figure 2.** Schematic layout of the laboratory with external walls of brick and hemp-lime.

The lime mortar for bedding and rendering used for all three walls was a natural hydraulic lime from St Astier NHL 3.5 mixed 1 to 1.5 with sand 0-4 mm (in volume). The hemp was supplied by BAFA Neu GmbH in Germany. Lime for the hemp-lime was an air lime (Nordkalk SL). The hemp and lime were mixed in a horizontal cement mixer on site. The parts by volume of the mix were 7 hemp to 4 lime to 4¼ water.

The three façade sections were built up as shown in Table 1 (see also Figure 2).

**Table 1.** Built-up of the masonry walls, starting with the external material.

**Façade A – Single leaf masonry wall**

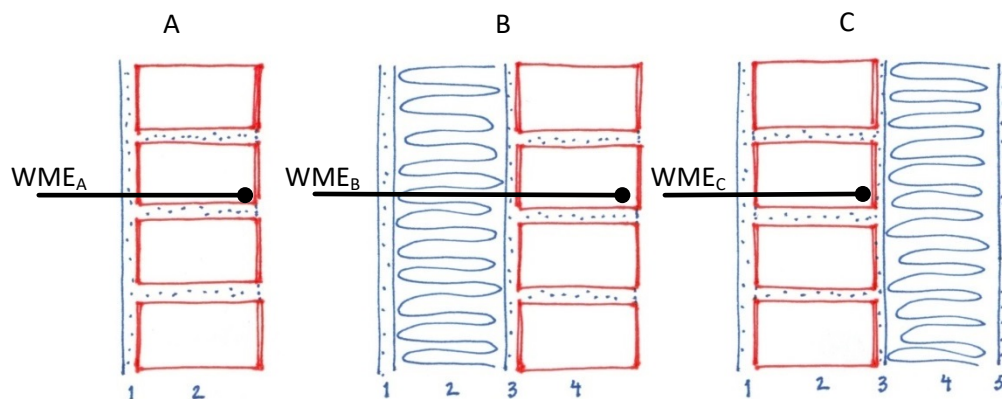
1. Lime plaster, 22 mm
2. Single leaf brick 120 mm

**Façade B – Internal hemp-lime insulation**

1. Lime plaster 22 mm
2. Hemp-lime 100 mm
3. Lime plaster 10 mm
4. Single leaf brick 120 mm

**Façade C – External hemp-lime insulation**

1. Lime plaster 22 mm
2. Single leaf brick 120 mm
3. Lime plaster 10 mm
4. Hemp-lime 100 mm
5. Lime render 22 mm



**Figure 3.** Three test façades at the BML-lab; A) single leaf masonry façade, B) single leaf masonry with internal hemp-lime and C) single leaf masonry with external hemp-lime. WME indicates the depth of the measurement of wood moisture equivalent (WME).

### 2.1. Moisture levels in the masonry

Moisture content in the masonry was measured using electrodes that were fitted 3 cm apart in the masonry at two depths inside each wall, see Figure 3. The electrodes were connected to wireless sensors (Omnisense) in combination with a wireless Gateway (Omnisense). Moisture content could be measured as wood moisture equivalents (WME). Specimens from the same brick as was used in the



test façades was used to determine moisture content at different relative humidities. Dry density of the brick was determined by means of drying and weighing three specimens. Dry density of the hemp-lime was determined by drying and weighing six specimens (100×100×100 mm). Thermal conductivity of the hemp-lime and brick was determined using a Thermal Constants Analyser (TPS1500, Hot Disk®).

The test specimens were conditioned at three different relative humidities in climate boxes. A fourth relative humidity level was accomplished using a climate chamber ( $\bar{T}=20.4^{\circ}\text{C}$  and  $(\bar{RH}=60.7\%)$ ). Relative humidity (RH) inside the climate boxes was kept at a constant level using salt solutions. Three different salt solutions were used, see Table 2.

**Table 2.** Relative humidity at saturation for different salt solutions, according to Greenspan [10].

Salt solution	Relative humidity [%] at saturation at 20°C.
NaCl	75.5
KCl	85.1
KNO <sub>3</sub>	94.6

The specimens were only conditioned at absorption. Three specimens per relative humidity were used. The specimens were weighed once they had reached equilibrium. Directly after weighing they were sealed in small plastic bags, one bag per specimen. The same was done for specimens that had been allowed to dry in a heat cabinet (105°C) until they reached equilibrium. An additional level of relative humidity was accomplished by putting the specimens in a layer of water inside a climate box and letting them take up water by means of capillary suction. Once the upper surfaces of the specimens were wet, they were regarded as having reached 100 % RH. The specimens were then taken out of the climate box, weighed, and sealed in plastic bags. Thus, in this study capillary saturation was defined as 100 % RH.

After weighing, electrodes were fitted 3 cm apart in the specimens and they were then directly transported to the lab inside a thermally insulated box. The wireless sensors at the lab were disconnected from monitoring the façades, and connected to the brick specimens. This way the measured moisture content (WME) could be related to the different levels of relative humidity. After measuring in the lab the specimens were dried to establish their dry weight. Using these weights the moisture content by mass at absorption ( $u$ ) could be calculated using equation (2);

$$u = \frac{m_1 - m_0}{m_0} \cdot 100\% \quad (2)$$

$m_1$  = mass at equilibrium with the surrounding relative humidity (g)

$m_0$  = dry weight (g)

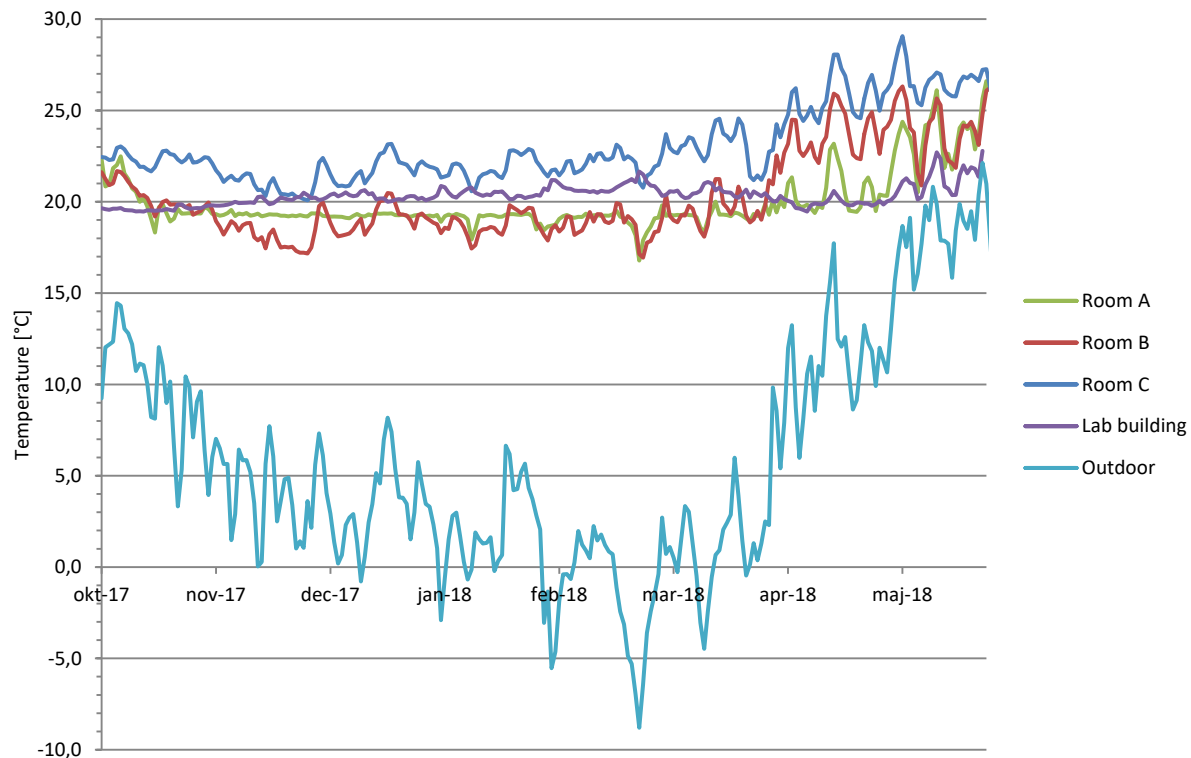
$u$  = moisture content (%)

### 3. Results and Discussion

#### 3.1. Energy performance

At the first day of monitoring, the 10th of October 2017, the average outdoor temperature was 6.4°C which meant that all three rooms required energy use for space heating from the start. Unfortunately, a system error occurred in February 2018 which meant that no data was available for energy use for space heating during the period 1-5 February 2018.

Temperatures inside the rooms as well as inside the lab building and the outdoor temperature were monitored. Four measured values per hour were converted into mean daily values, see Figure 4.



**Figure 4.** Mean daily temperature in the three test rooms, the surrounding lab building and outdoors during the monitored period 10 Oct 2017-26 May 2018.

For room A, a PID-controller (proportional–integral–derivative controller) was installed that kept the indoor temperature relatively stable even though the masonry façade was not thermally insulated. The PID-controller was situated outside of the room, in the surrounding lab. Room B and C that both had 100 mm hemp-lime as thermal insulation did not need to have a PID-controller installed. Mean daily temperatures for the entire monitoring period were as shown in Table 3.

**Table 3.** Mean daily temperatures and their SD measured by HOBO in the three test rooms, the surrounding lab building and outdoors from 10<sup>th</sup> October 2017 to 26<sup>th</sup> May 2018.

Room A, °C	Room B, °C	Room C, °C	Lab building, °C	Outdoor, °C
19.8 ± 1.8	19.9 ± 2.3	22.6 ± 2.0	20.3 ± 0.6	5.8 ± 6.8

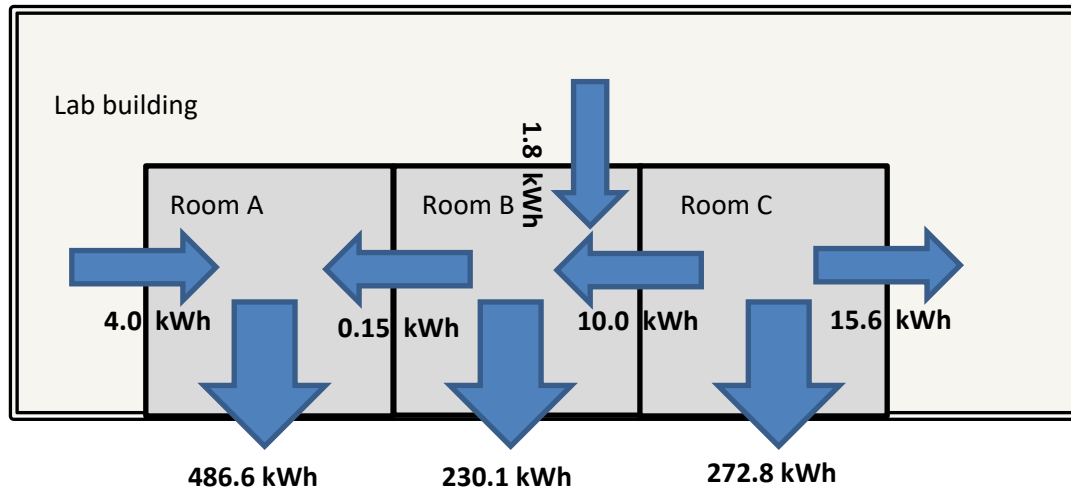
As there were some temperature differences between the rooms and also between the rooms and the surrounding lab building (see Figure 5) there were some energy gains and losses in the rooms that need to be taken into account. Temperature difference ( $\Delta K$ ) between the rooms as well as between the rooms and the surrounding lab building were determined for each day, and then multiplied by 24 hours (h) to get the degree hours difference.

$$\Delta K \cdot h = (\bar{T}_{room\ 1} - \bar{T}_{room\ 2}) \cdot 24 \quad (3)$$

The U-value for the internal walls was 0.28 W/m<sup>2</sup>K. The energy loss/gain through the internal walls was then calculated as follows;

$$\frac{W}{m^2 \cdot K} \cdot (\Delta K \cdot h) = \frac{W \cdot h}{m^2} \quad (4)$$

$$kWh = m^2 \cdot \frac{kW}{m^2 \cdot K} \cdot (\Delta K \cdot h) \quad (5)$$



**Figure 5.** Energy flows between rooms and through the façades.

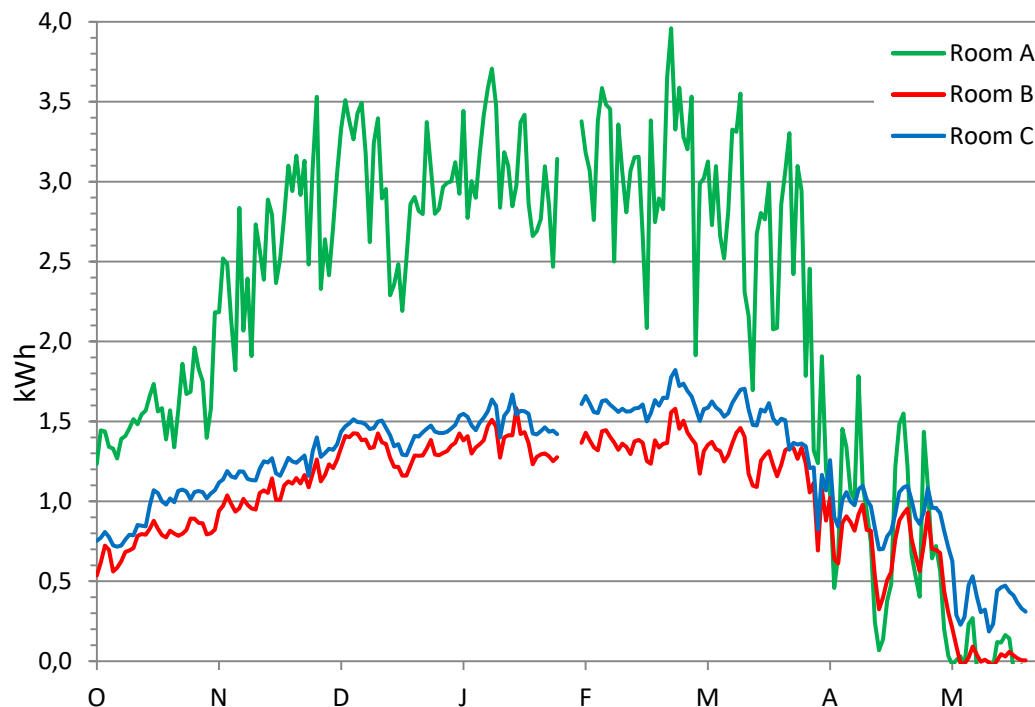
The total energy use for space heating was thus 486.6 kWh for room A with a single leaf masonry façade, 230.1 kWh for room B with internal hemp-lime insulation and 272.8 kWh for room C with external hemp-lime insulation. Daily mean values of energy use for space heating are shown in Figure 6. There is a clear improvement of energy performance when hemp-lime insulation is applied to the masonry. Some material properties are shown in Table 4.

**Table 4.** Measured density and thermal conductivity for the brick and hemp-lime.

Material	Density, kg/m <sup>3</sup>	Thermal conductivity, W/mK
Hemp-lime	453.8	0.14
Brick	1707.0	0.65

Comparing the rooms that had been insulated with hemp-lime to the room with the uninsulated single leaf masonry façade the improvements in energy performance are as follows; 44 % improvement for the room with external hemp-lime and 53 % improvement for the room with internal hemp-lime insulation. It was somewhat unexpected that the room with internal hemp-lime performed a bit better, as the hemp-lime had not been able to dry after the building process. The rooms behind the façades were not ventilated, they were only heated. Therefore the internal hemp-lime could not easily dry towards the indoors, leaving a material with higher moisture levels than what would have been possible if the room would have been ventilated. Even so, this façade thermally outperformed the façade with external hemp-lime.





**Figure 6.** Energy use for space heating (daily mean values) of the three test rooms during the heating season.

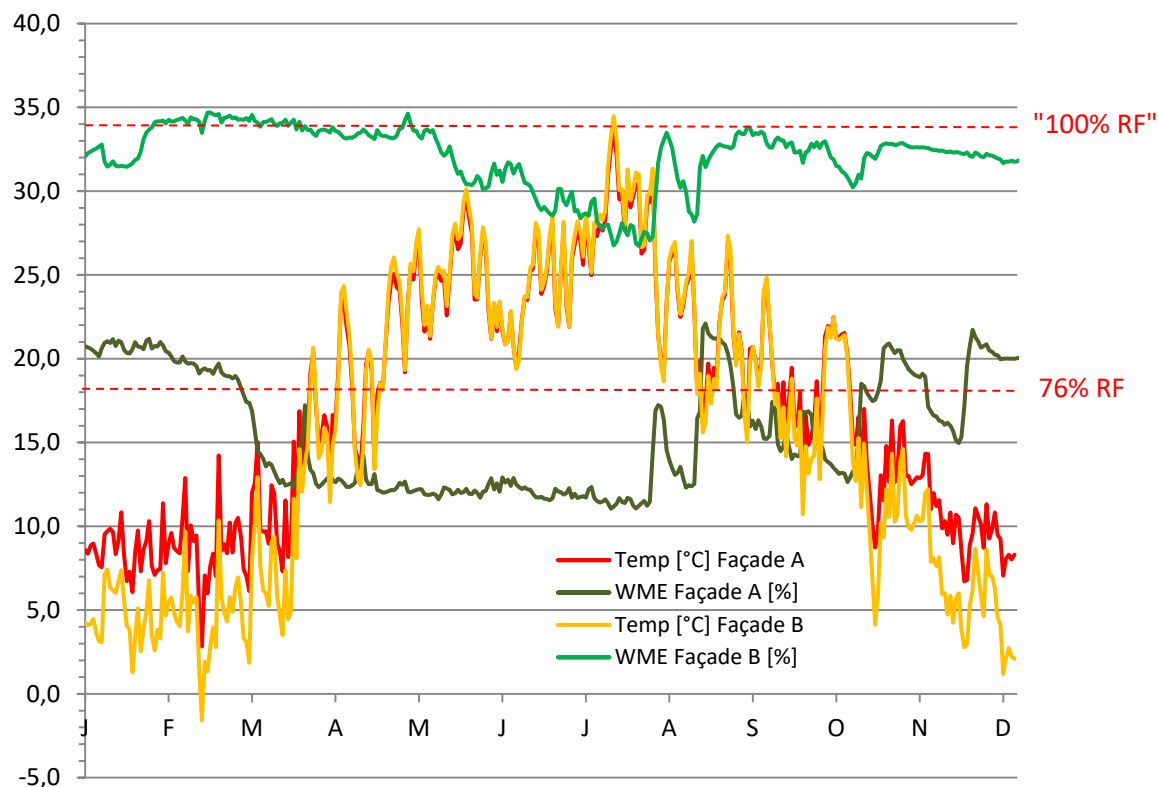
### 3.2. Moisture levels in the masonry

Lab measurements gave the correlation between measured wood moisture content (WME) and the relative humidity in the brick, see Table 5. For higher relative humidities this correlation was quite diffuse, with relatively large standard deviations. Therefore no conversions were made from WME to relative humidity in the brick. Rather, this correlation should be viewed as an indication of approximately relative humidities in the brick, where higher WME also indicates higher RH. Even so, the WME levels that correlate to 75.5 % RH and “100% RH” (capillary saturation) are shown in Figures 8 and 9 to give an approximate indication of moisture levels in the brick.

**Table 5.** Measured WME [%] in the brick and their standard deviations, at different relative humidities [%]. Three measurements per RH.

RH [%]	WME [%]
0	$9.0 \pm 0.4$
60.7	$16.3 \pm 0.6$
75.5	$18.2 \pm 3.8$
85.1	$18.6 \pm 3.7$
94.6	$19.9 \pm 2.1$
“100”	$33.9 \pm 1.1$

Moisture content and temperature measurements inside the brick started later than the energy use measurements. WME and temperature in the brick was monitored for almost a year; from the 17th of January to 17th December 2018, see Figures 7 and 8. WME and temperature were measured at the external surface of the brick, see Figure 7.

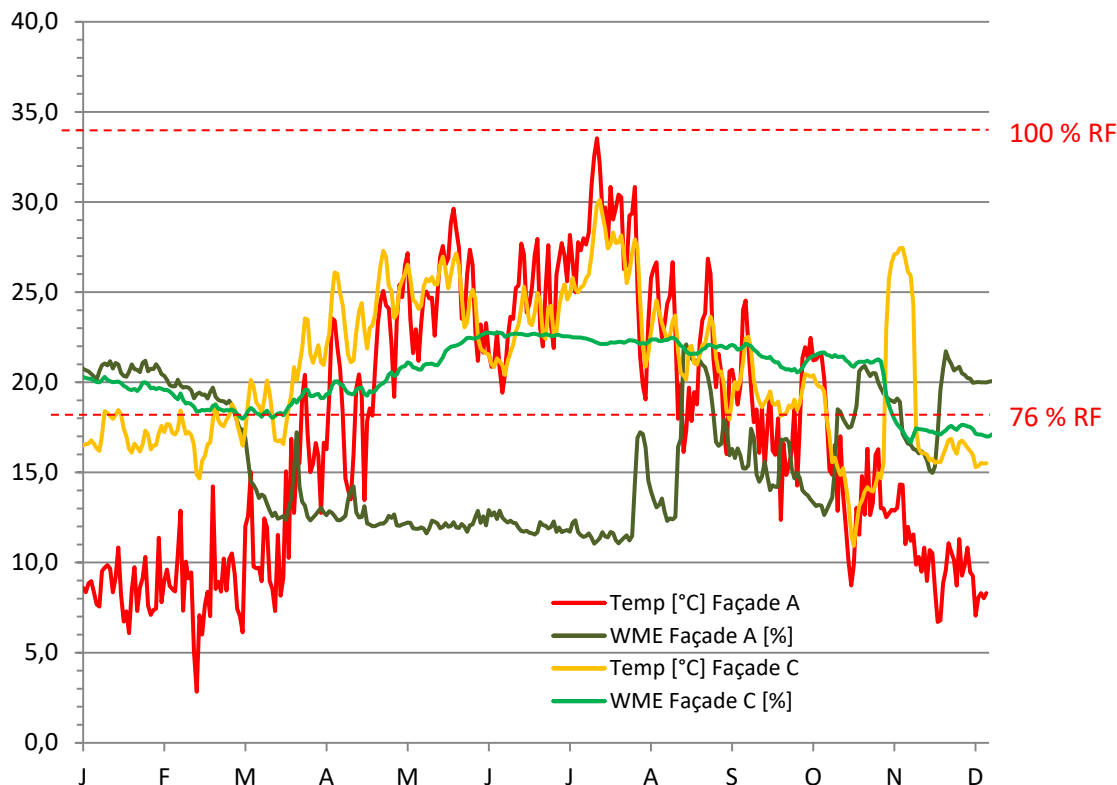


**Figure 7.** Temperature and WME [%] at the surface of the brick for a single leaf masonry wall (Façade A) and for a single-brick wall with 100 mm internal hemp-lime insulation (Façade B).

Comparing a single-leaf masonry façade to a façade with 100 mm internal hemp-lime insulation there is a large difference in moisture levels in the masonry. While moisture levels are rather low in the single-leaf masonry façade (façade A), the moisture levels in the masonry with internal hemp-lime insulation (façade B) are quite high. In winter they reach, and go beyond, a level that was measured for capillary saturated brick samples (“100 % RH”). Additionally, the temperature in the masonry of façade B was lower than that in façade A. While the surface temperature in façade A stays above 0°C during the entire winter, the temperature in façade B reaches freezing temperatures during a cold spike in February. Higher moisture levels in combination with lower temperatures in the masonry brings about an increased risk of frost scaling.

A contributing factor to the high moisture levels in façade B was the lack of ventilation of the room behind the façade. The building moisture from the hemp-lime could not dry inwards, which likely has had an effect on moisture levels in the entire façade. However, there are very large differences between the moisture levels in the masonry of the two façades strongly indicating that internal hemp-lime insulation will lead to higher moisture levels in the masonry and to lower temperatures in the masonry. This combination can lead to an increased risk of frost scaling. However, during visual inspection of the masonry façades no frost-scaling damage could be found.

Either way, in a cold climate like in Sweden masonry materials must be designed to be frost resistant, and historic masonry in need for thermal insulation has often already proven if it is frost resistant or not.



**Figure 8.** Temperature and WME [%] at the surface of the brick for a single leaf masonry wall (Façade A) and for a single-brick wall with 100 mm external hemp-lime insulation (Façade C).

Comparing the single leaf masonry façade (façade A) to a façade with 100 mm external hemp-lime insulation (façade C) there is a clear difference in temperatures inside the masonry, with the externally insulated masonry having higher temperatures during the cold season and lower temperatures in summer. This is what would be expected when externally insulating the masonry. Moisture levels in façade C were similar to those in the single leaf masonry façade. But while façade A continued to dry during the spring and summer, moisture levels in façade C increased somewhat. This indicates that some of the moisture from the external hemp-lime dried inwards and increased moisture levels in the masonry. The temperature spike in November was caused by a failure in the heating system, causing an increase in room temperature in room C. As a consequence, moisture levels in the masonry of façade C decreased. In December moisture levels in the single leaf masonry façade increased while those in façade C remained rather low.

#### 4. Conclusions

Thermally insulating historic masonry walls with hemp-lime can lead to substantial improvements in energy performance. Results from the studies performed for this paper gave an improvement in energy performance of 44-53 % when insulating a single leaf masonry wall with 100 mm hemp-lime. This will most likely also have a positive effect on the indoor climate.

When evaluating the results, it is important to bear in mind that most historic masonry buildings constructed since the beginning of the 19th century have been constructed using considerably thicker brick masonry, at least 1-stone but often 1½-stone or 2-stone width. These masonries does not always allow a thick additional insulation layer in their construction, but since they are often lime-plastered, at least internally, with a thick plaster there is often a given thickness of lime mortar that could be replaced with hemp-lime instead. The difference in energy efficiency and moisture transport follows the thickness of the hemp-lime for each specific case. What can be concluded is that with an additional

insulation of hemp-lime on brick masonry, the thermal performance is improved very clearly. At the same time, it is an addition that allows a continued use of lime render/lime plaster as a surface treatment and that the masonry remains having a moisture and heat flow as before. Given that the initial building moisture can dry out, it presumably works well to insulate a brick wall with hemp lime, both internally and externally.

However, moisture levels in the masonry were high in the masonry insulated with hemp-lime. In combination with lower temperatures in the masonry, as was the case in the façade with internal hemp-lime insulation, this may increase the risk for frost scaling if the materials are not frost resistant. High moisture levels in the façade with internal hemp-lime insulation were most likely partly caused by the absence of ventilation in the room behind the façade, with limited possibilities of the hemp-lime to dry inwards. It is important to allow the hemp-lime to dry after construction.

The appearance of the building façade and its heritage values can be preserved, which is a valid argument for using internal insulation. When retrofitting historic masonry façades with internal hemp-lime it should be considered to use a layer of less than 100 mm hemp-lime insulation, in order to improve energy performance of the masonry façade while at the same time avoiding moisture damage and frost scaling problems.

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