Hygrothermal performance of a massive natural stone masonry wall insulated from the internal side with hemp concrete – field measurements in cold climate

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Abstract. Improving of exterior walls in historic and traditional buildings is often only possible with interior thermal insulation. The actual structure and material properties of the existing exterior wall are usually the main unknown factors. Therefore, field measurements with small mock-ups are helpful before large-scale renovation. The current study analyses by field measurements the hygrothermal performance of internally insulated massive stone wall. Two different hemp concrete mixes were developed for the insulation. Temperature and humidity conditions were measured periodically over one year period. Results showed a very low drying rate of hemp concrete interior insulation. The external side of hemp concrete insulation will stay moist for a very long period. Temperature of coarse hemp concrete was slightly higher during the cold period. Wooden studs used to install hemp concrete will stay in moist areas for a long period. Temperature drop below 0 °C shows that interior insulation should be durable for freezing-thawing cycles. Drying out of constructional moisture is absolutely necessary for hygrothermal design. Before considering large-scale renovations, it is necessary to further assess the long term durability and performance of hemp concrete in a moist environment. The temperature increase on the interior surface could slightly improve indoor thermal comfort.

1. Introduction
External walls of historic buildings (brick or natural stone) have a high thermal capacity due to their mass. Although brick buildings were already erected at the beginning of the Middle Ages, in Estonia bricks were used mostly in areas where a shortage of natural building stone was the case. Limestone and ore stone are the main natural stones used for construction in Estonia.

The thickness of natural stone walls usually starts at 500 – 700mm but can vary depending on the load bearing requirements. Thermal conductivity of massive stone masonry depends on the stone type, content of mortar and aggregate. Massive natural stone masonry has a high thermal transmittance and low surface temperature during heating season in cold climate. This causes a risk of exceeding the critical moisture levels, potentially resulting in surface condensation, mould growth, and low thermal comfort. Improving the situation would entail increasing moisture safety and thermal comfort while also reducing the amount of energy required for heating. Comparing energy balances of non-insulated and retrofitted walls, Maděra [1] has shown that the reduction of energy loss can reach up to 89%, depending on the type of the wall that is analysed.

Bottino-Leone [2] has analysed insulation retrofit strategies and shown that vegetal-based insulation systems have a significantly lower initial environmental impact than fossil fuel based materials, although
the operational environmental impact is similar for all retrofit variants. Hemp-lime concrete is a material that can be used to increase the energy efficiency, while reducing carbon footprint by using more locally produced raw materials [3]. Sebaibi et.al. [4] have shown that flax fibres and hemp aggregates can be used for non-autoclaved insulating foam using bio-based materials to achieve a thermal conductivity lower than 0.2 W/(m K). Costantine et.al. [5] used 130 mm hemp concrete as an external wall insulation with results showing acceptable thermal comfort but episodes of high relative humidity due behaviour of the inhabitants.

In most cases, external insulation is not acceptable in renovation of historic buildings. A possible solution to improve energy efficiency while preserving architectural appearance, lies in internal insulation. Ferrari et.al. [6] have analyzed the heat and moisture behavior of a solid brick wall in northern Italian climate, supposed to be insulated internally with five different materials: calcium silicate hydrates, fiberwood, expanded polystyrene, stone wool, and aerogel and found that the last three are the most favourable conditions for mould growth. Klõšeiko et.al. [7] compared the hygrothermal performance of different internal insulation materials - the same wall was insulated with four materials and found that PIR and IQ-T board exceeded the RH_{crit}'80' convincingly and AAC and CaSi exhibited almost equal absolute humidity behind the insulation, with the difference in RH due to lower thermal transmittance of the AAC layer.

Drying out of constructional moisture [8], racking due to freeze–thaw cycles of internal insulation [9,10], interstitial condensation or mould growth [11,12] are usually the most common failures for internal insulation of stone walls. Modelling, laboratory and field measurements are possible ways to study the performance of internally insulated massive stone walls. The actual material properties of the existing exterior wall are usually the main unknown factor in historic buildings. Therefore field measurements with small mock-ups are helpful before large-scale renovation. In the current study, this approach was used to assess the hygrothermal performance of an internally insulated massive natural stone masonry wall in Estonian cold climate.

2. Methods

2.1. Case study - Stable and carriage shed in Mooste manor

Stable and carriage shed the complete Mooste manor ensemble (Figure 1) is an example of ore stone architecture. The building is one of the oldest in the manor complex, probably dating from the first half of the 19th century [13].

Figure 1. The case-study building before (above, 2017) and after (2020, below) the restauration.
The manor's stable and carriage shed is a large rectangular natural massive stone building with a pitched roof. The roof structure is made of wood and partly original. The external walls of the building are laid from massive ore stone using lime mortar. The façade is levelled using lime plaster, leaving the protruding stones partially visible.

![Figure 2. Plan of the building. M1:250.](image)

The building was renovated into a competence centre for sustainable construction, raising expectations for indoor climate and the need to reduce heat loss from the building. Hemp concrete is planned for internal insulation to reduce thermal transmittance and increase the internal surface temperature of external walls. Among other insulation materials, hemp concrete was proposed as a renovation measure by Ziegert | Seiler Ingenieure GmbH [8].

2.2. Test section

Current study analyses by field measurements the hygrothermal performance of an internally insulated section of a massive stone wall with a thickness of 700mm. Temperature and relative humidity at stone surface and in mid-insulation were measured over a 1-year period.

Two different hemp concrete mixes were used to comparatively assess the possible effects of hemp shiv size on hygrothermal behaviour of hemp concrete. The binder used was traditionally produced lime putty with an average water content of 50%. Fine vacuum-packed hemp shiv (10-15mm) and loose coarse hemp shiv (15-30mm) were used as aggregates for fine and coarse hemp concrete respectively.

The hemp concrete was prepared in the following sequence: First, 10 litres of lime putty and 10 litres of water were mixed together until a uniform consistency was achieved. Adding 40 litres of dry hemp shiv, the ingredients were mixed until reaching sufficient saturation. This is indicated by the hemp shiv sticking together as excess moisture is absorbed. When this occurs, the glistening reflection of water on the surface of the hemp shiv becomes less visible and the mix will form clumps more readily when turned. In the case of coarse hemp concrete, water volume was increased to 150\% to achieve sufficient saturation and mix workability.

Test bodies were also made for laboratory assessments of water absorption (EN 1015-18), water vapour absorption (EN 12571) and water vapour permeability (EN 12572) of coarse and fine hemp concrete. Calculated dry density, based on the samples, was 240 kg/m\(^3\) for coarse and 360 kg/m\(^3\) for fine hemp concrete. Results of assessments are described in more detail by Ruus et al. [14].
To vertically align the desired surface of the insulation, wooden posts with a cross-section of 50x50mm were attached to the stone wall using brass and steel anchoring. The distance of hemp concrete surface from the uneven stone surface varied from 150 to 200mm. Water resistant plywood was used to seal both sides of the entire test section and to separate the two different hemp concrete mixes in the middle. Waterproof isolation tape (Gerband 586 Hermetic) was used to seal gaps between the stone wall and plywood.

Temperature and relative humidity inside the insulation was periodically measured over the course of a year after casting the hemp concrete, using HOBO UX100-023 External Temperature/Relative humidity loggers. To provide insight about possible temperature and humidity extremes and fluctuations, a 16-day period of winter cold (up to -21°C) was more closely monitored. The room temperature was maintained at 12°C throughout the 16-day measuring period. All 10 internal measurement locations are shown on figures 5 and 6.

Figure 3. Horizontal section (B-B on figure 5). Measuring locations FHCL2 and FHCL3 are set by casting protective plastic tubing inside the hemp concrete insulation.

Figure 4. Drilling locations at 200mm and 1200mm height for moisture samples.

Figure 5. Vertical section of the test wall (A-A on Figure 6): °C and RH% sensor locations indicated by red squares.

To assess the moisture distribution within the insulation, samples were taken with a 100mm core drill from both insulation fractions at heights of 200 and 1200 mm measured from floor level (Figure 4). Each sample was divided into four sections: The outermost 40-50mm of the insulation could be removed as a solid disc in all four drilling locations. This was followed by 100-150mm of uncarbonized hemp concrete that could only be removed as loose material. This was done in three separate stages to allow for the comparison of moisture content by sample depth. All samples were weighed at the site, dried in an oven for 2h and then weighed again. The resulting difference in the weight of the samples is shown in Figure 9. Fine hemp concrete contained 20% and coarse hemp concrete 30% water by volume – the minimum amount required in each case to achieve a workable mix.
3. Results

After one year after hemp concrete installation, it is still wet – pore humidity is over saturation i.e. RH stayed 100% in all measuring points. At 500mm (see Figure 7), the minimum temperature on the stone wall was -1.4°C at CHCL3 and -0.9°C at FHCL3. Lowest mid-insulation temperatures at 500mm height measured were 2.5°C at CHCL2 and 1.9°C at FHCL2.

At 1500mm height (see Figure 8), the lowest measured temperature at stone surface was -1.2°C in coarse hemp concrete (CHCU3) and -1.4°C in fine hemp concrete (FHCU3). The lowest mid-insulation temperature in coarse hemp concrete at 1500 mm (CHCU2) was 3.1 °C and in the middle of fine hemp concrete (FHCU2) the minimum temperature was 2.8 °C.

During the cold period (14.01 - 29.01.2021), the minimum external temperature was measured at -21°C. The temperature difference between stone surface (CHCU3; FHCU3) and hemp concrete surface (CHCU1; FHCU1) became more noticeable during the cold period. The lowest measured temperature on hemp concrete surface was 9.1 °C at CHCU1 and 8.2 °C at FHCU1.

Continued assessments are required to determine the necessary time period for the drying out of excess moisture and its effect on thermal transmittance of CHC and FHC test sections. The results of yearly temperature and relative humidity measurements are shown in Figures 7 and 8.

Figure 6. Horizontal section of test wall (B-B on Figure 5): temperature and RH sensor locations indicated by red squares.

Figure 7. Measured temperature and relative humidity values at 500mm height. External temperature and RH are presented as daily average values).
Figure 8. Measured internal temperature and relative humidity values at 1500mm height. External temperature and RH are presented as daily average values).

Upon weighing the samples after drying, the moisture content was lowest in samples taken at 200mm height, from 0-40mm depth (CHCL4 – 17%; FHCL4 – 19%). For all other samples the moisture content varied between 35% – 42%. These results are illustrated in Figure 9.

Figure 9 Moisture content in the cross-section samples from 4 drilling locations in the hemp concrete insulation after 1.5 year of installation the hemp concrete.

1.5 years after the installation of the hemp concrete, it become was heavily contaminated with several different mould species. The deterioration penetrated through entire depth of the plaster layer. Dominating species occurred from genus’s *Trichoderma* and *Cladophialophora*.

4. Discussion
As thermal transmittance of insulation materials is noticeably affected by their hygric performance, the approach described herein is aimed at building an initial framework for more detailed and long-term in-situ assessments in this field. The effect of shiv size and water content on the hygrothermal performance of hemp concrete insulation in cold climate are topics that require further assessment.

Elevated surface temperature during cold periods is one of the goals when aiming to increase thermal comfort in historic stone buildings. Coarse hemp concrete showed slightly higher surface temperature during the cold period than fine hemp concrete. As the drying process continues, further measurements should be compared to other in-situ research in similar conditions to provide validation.
As the water content by volume in coarse hemp concrete was ca 150% compared to fine hemp concrete, this difference in total amount of water in each test section is an important factor in their actual hygrothermal performance.

An important aspect not studied in this work is the effect of high moisture content on the integrity and possible degradation of internal hemp concrete insulation. Klöseko et al. have emphasised the importance of accounting for the moisture levels caused by the construction process. The report “Investigation and technical concept for conservation works and building physics” by Ziegert | Seiler Ingenieure GmbH [15] did not take into account the water content of the mix upon application.

As pore air relative humidity in coarse and fine hemp concrete remained at 100% during 1 year after installation, the long-term effects of moisture added during construction should not be overlooked. Sinka et al have shown that redundant water in hemp concrete can increase thermal transmittance by 25-33% [8]. The time period required for the drying of construction moisture in the described case is unknown.

Results showed a period of negative temperature on the stone surface, bringing into focus the effect of freeze-thaw cycles on moisture-saturated hemp concrete. Laboratory and in-situ tests should be carried out to provide further insight in this field.

According to the literature [16–18] biodeterioration of hemp composite plaster (or concrete) may occur when moisture/water what is essential in activating the reactive elements within the binders stays surplus long time after installation of plaster. Microorganisms, producing extracellular enzymes, are able to grow on natural fibres when subjected to moist environmental conditions in all stages of life cycle – starting from harvesting up to in situ in installed constructions. This potential risk should be taken into consideration when designing, manufacturing and installing materials containing natural fibres. Deteriorated plaster layer must be removed. Regarding the potential health risk, precautionary measures should be taken when removing the plaster. Also, disinfection of the wall is also necessary to execute.

5. Conclusion
Hemp concrete stayed moist over long period and drying out of constructional moisture was very slow. One year after installation the hemp concrete, relative humidity was 100% in all measuring locations. Therefore it become heavily contaminated with several different mould species. Thus, the production and application method described herein are not recommended for internally insulating fieldstone buildings under similar conditions.

The solution is not immediately recommended for use in cold climates. Temperature drop below 0 °C shows that interior insulation should be durable for freezing-thawing cycles. Drying out of constructional moisture is absolutely necessary for hygrothermal design. Before considering any large-scale renovations, it is necessary to further assess the long term durability and hygrothermal performance of hemp concrete in a moist environment.

The surface temperature of coarse hemp concrete was slightly higher. From this perspective, using coarse rather than fine hemp concrete for internally insulating historic stone buildings, seems better aligned with the aim of improving their indoor thermal comfort. Further comparative in-situ assessments are required to validate these tentative findings and to determine the combined effect of shiv size and water content in hemp concrete on the indoor climate in historic stone buildings. These criteria can be assessed more accurately when excess moisture has dried out from the hemp concrete.

Acknowledgments
This research was supported by the Estonian Centre of Excellence in Zero Energy and Resource Efficient Smart Buildings and Districts, ZEBE (grant No. 2014–2020.4.01.15-0016) and funded by the European Regional Development Fund, by the Estonian Research Council (grant No. PRG483), and by the European Commission through the H2020 project Finest Twins (grant No. 856602).

References
[1] Maděra J, Kočí V and Černý R 2017 Computational analysis of the energy efficiency of stone walls: Current situation and possible improvements International Journal of Sustainable Development and Planning 12 264–72
Bottino-Leone D, Larcher M, Herrera-Avellanosa D, Haas F and Troi A 2019 Evaluation of natural-based internal insulation systems in historic buildings through a holistic approach *Energy* **181** 521–31

Sinka M, Bajare D, Gendelis S and Jakovics A 2018 In-situ measurements of hemp-lime insulation materials for energy efficiency improvement *Energy Procedia* vol 147 (Elsevier Ltd) pp 242–8

Sebaibi N, Khadraoui-Mehir F, Kourtta S and Boutouil M 2020 Optimization of non-autoclaved aerated insulating foam using bio-based materials *Construction and Building Materials* **262** 120822

Costantine G, Maalouf C, Moussa T, Kinab E and Polidori G 2020 Hygrothermal evaluation of hemp concrete at wall and room scales: Impact of hysteresis and temperature dependency of sorption curves *Journal of Building Physics* **44** 183–224

Ferrari S and Riva A 2019 Insulating a Solid Brick Wall from Inside: Heat and Moisture Transfer Analysis of Different Options *Journal of Architectural Engineering* **25** 04018032

Klöšeko P, Arumägi E and Kalamees T 2013 Hygrothermal performance of internally insulated brick wall in cold climate: field measurement and model calibration *Proceedings of 2nd Central European Symposium on Building Physics* (Vienna: Vienna University of Technology)

Klöšeko P, Kalamees T, Arumägi E and Kallavus U 2015 Hygrothermal Performance of a Massive Stone Wall with Interior Insulation: An In-Situ Study for Developing a Retrofit Measure *Energy Procedia* vol 78

Klöšeko P, Varda K and Kalamees T 2017 Effect of freezing and thawing on the performance of “capillary active” insulation systems: A comparison of results from climate chamber study to HAM modelling *Energy Procedia* vol 132

Zhou X, Derome D and Carmeliet J 2017 Hygrothermal modeling and evaluation of freeze-thaw damage risk of masonry walls retrofitted with internal insulation *Building and Environment* **125** 285–98

Klöšeko P, Arumägi E and Kalamees T 2015 Hygrothermal performance of internally insulated brick wall in cold climate: A case study in a historical school building *Journal of Building Physics* **38**

Klöšeko P and Kalamees T 2016 Case study: In-situ testing and model calibration of interior insulation solution for an office building in cold climate *CESB 2016 - Central Europe Towards Sustainable Building 2016: Innovations for Sustainable Future*

Nõmmemaa M 2009 *Special conditions for heritage protection for conservation of Stable and carriage shed in Mooste manor* (Tartu)

Ruus A, Koosapoe T, Pau M, Kalamees T and Põldaru M 2021 Influence of production on hemp concrete hygrothermal properties: sorption, water vapor permeability and water absorption *8th International Building Physics Conference - IBPC2021* (25-27 August 2021. Copenhagen, Denmark)

Ziegert C *Investigation and technical concept for conservation works and building physics* (Mooste, Estonia)

Crawford B, Pakpour S, Kazemian N, Klironomos J, Stoeffler K, Rho D, Denault J and Milani A S 2017 Effect of fungal deterioration on physical and mechanical properties of hemp and flax natural fiber composites *Materials* **10** 1252

Malinicova E, Hrehova L, Cigasova J, Stevulov N, Schwarzova I, Gaper J, Javorsky P and Pristaš P 2018 Molecular characterization of myxomycetes and fungi colonizing hemp hurds in water environment *Asian Journal of Microbiology, Biotechnology & Environmental Sciences Paper* **20** 84–9

Arizzi A, Brümmer M, Martín-Sanchez I, Cultrone G and Viles H 2015 The influence of the type of lime on the hygric behaviour and bio-receptivity of hemp lime composites used for rendering applications in sustainable new construction and repair works *PLoS ONE* **10** e0125520