Moisture Buffering of Hemp-Lime with Biochar and Rape Straw-Lime as Surface Materials for a Stable Indoor Climate

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Abstract. An appropriate and stable indoor climate in museums is crucial to guarantee an appropriate preservation of our cultural heritage. Depending on the collection, indoor temperature and relative humidity need to be kept within a certain range. Fluctuations in temperature and relative humidity could cause damage to museum artefacts and may require higher energy needs than necessary. Biochar is a material of which the use is relatively new in building materials. Previous studies have shown that biochar has unique moisture properties with a high surface area, high porosity and therefore high capability of moisture uptake. In Southern Sweden there are several biochar manufacturers that produce biochar from local biomasses such as seaweed, gardening wastes and residues from greenhouses.

The aim of this project was to investigate the impact of hygroscopic surface materials on the indoor climate of buildings, focusing on moisture buffering and hygrothermal properties. The building materials that were studied were hemp-lime (with and without biochar) and rape straw-lime. Passively influencing the indoor climate by choosing appropriate surface materials could contribute to lower energy needs and less need for mechanical ventilation in historic buildings and museums without the need for excessive HVAC solutions.

Keywords: Hemp · Rapeseed · Lime · Historic Buildings · Thermal Properties

1 Introduction

Traditional building materials used in the interior of historic buildings have different material properties than many conventional materials due to their hygroscopic nature. Also, historic artefacts often consist of different materials with different hygroscopic properties [1]. With moisture absorption the materials swell and shrink and as they change size objects will deteriorate faster. A stable climate without moisture fluctuation therefore would provide better conditions for preservation. If the building itself is made of hygroscopic materials with a high moisture buffering capacity they could contribute and help providing a more stable relative humidity (RH) in the air [2]. The aim of this study was to see if novel bio-based materials with high moisture buffering properties can

S. Amziane et al. (Eds.): ICBBM 2023, RILEM Bookseries 45, pp. 144–157, 2023.
https://doi.org/10.1007/978-3-031-33465-8_12

be an alternative as surface materials on plastered walls and roofs in historic buildings i.e. churches, castles and local museums. Many of those buildings have a low temperature in winter and the moisture levels can thus be higher than preferred. In this study the moisture buffering properties are investigated of hemp-lime, of hemp-lime with an addition of biochar as well as of rape straw-lime.

Previous research has shown that hemp-lime has an "excellent" moisture buffer value [3 4 5]. According to the classification in the Nordtest protocol, a material with "excellent" moisture buffering has a moisture buffer value greater than 2.0 kg/(m^2·% RH). Hemp-lime is a building material in which hemp shiv (the woody core parts of the hemp stem) are used in combination with building limes. Hemp-lime has been tested as additional insulation and is compatible with historic wooden houses as well as historic masonry [6, 7]. The material has both good thermal insulation and relatively high thermal inertia. Studies have also shown that it can contribute to a good indoor environment due to its acoustic properties as well as its good fire resistance [8–10]. The fact that the material also has a low climate impact makes it interesting for the transition towards more sustainable building constructions.

Hemp-lime is a hygroscopic material that can be used as a visible internal surface layer on walls and in roofs or, more commonly, as a base layer for a thin lime plaster surface finish in historic buildings.

1.1 Hemp-Lime and Rape Straw-Lime

Rapeseed (Brassica napus and Brassica rapa) and hemp (Cannabis sativa) are agricultural crops cultivated in Sweden. Statistics from the Swedish Board of Agriculture [11, 12] state that the total acreage cultivated in 2022 was 127,500 ha rapeseed (both Brassica napus and Brassica rapa), see Fig. 2. The same year 222 ha hemp was cultivated, see Fig. 3. Rapeseed is a significant oilseed crop in Sweden, while hemp cultivation is not as common. Hemp cultivation was prohibited in Sweden from the 1965 until 2003 [13], which caused knowledge on hemp cultivation techniques to vanish, as well as the commercial market for hemp seed, hemp fiber and hemp shiv. Since 2003 hemp cultivation has been allowed again in Sweden. In 2007 hemp cultivation peaked at 828 hectares. Since then, hemp cultivation has been approximately 200 ha annually. Today, hemp-lime is used for construction in Sweden on a modest scale, with a handful of hemp-lime houses built in southern Sweden. For hemp-lime the hemp shiv are used, which are the woody core parts of the hemp stem, see Fig. 1. When not used in construction, hemp shiv are commonly used for animal bedding. Rape straw-lime is a material that consists of chopped rape straw that is used in combination with building limes, in a similar fashion as the production of hemp-lime. For rape straw-lime (to our knowledge thus far not used in Sweden for construction) the straw of rapeseed was used, see Fig. 1.

Because of the greater abundance of rape seed in Sweden, residues from rapeseed cultivation would be interesting for use in building materials. Nowadays rape seed straw is usually ploughed under in the field to improve soil structure and add nutrients to the soil (so-called soil incorporation) or used as animal bedding [14].

The use of biomass from agriculture in building materials is advantageous in multiple ways. The building sector benefits from the production of building materials with a low environmental impact as increasing the biobased material content of a building generally

Fig. 1. Hemp shiv to the left, rape seed straw to the right.

results in a reduced climate impact if the biogenic carbon sequestration is accounted for in the life-cycle analysis [15]. Biobased residue materials from agriculture are renewable; new material can be cultivated each year. At the same time, the agricultural sector benefits from finding a commercial market for its residue materials.

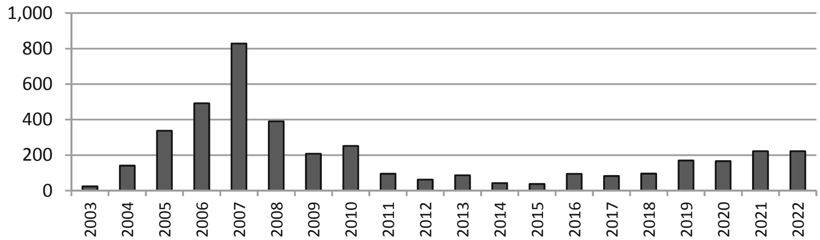

Fig. 2. Hemp cultivation (hectares) in Sweden 2003–2022 [11].

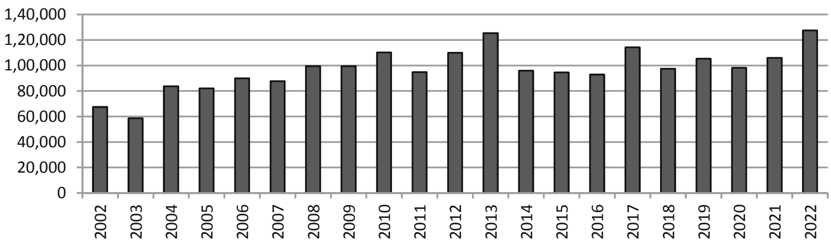

Fig. 3. Rape seed cultivation, Brassica napus and Brassica rapa, in Sweden 2002–2022 [12].

1.2 Biochar

Locally sourced seaweed (macroalgae) was used to produce the biochar used in this study. Seaweed from the Baltic Sea was collected at the shoreline of Trelleborg municipality, on the southern coast of Sweden. Every year problems arise with seaweed at the shoreline of Trelleborg municipality. These seaweed-related problems entail inconveniences for beach visitors such as difficulties to reach the beach because of beach-cast seaweed and an unpleasant smell, economic problems that arise when removing the seaweed, and loss of income from tourists that stay away. But mostly the seaweed accumulation leads to, and is amplified by, ecological problems such as eutrophication and biodiversity loss [16]. At the same time, seaweed is a material resource that is available in abundant amounts. Therefore, Trelleborg municipality is searching for ways to upcycle seaweed harvested from its shoreline and put it to use in a different function, such as biogas [16] or biochar [17]. The biochar in this study was produced by Skånefrö AB in Hammenhög, southern Sweden. The biochar was produced through pyrolyzing biomass (in this case seaweed) by subjecting it to high temperatures in the absence of oxygen, thereby causing thermal decomposition of the biomass [17].

Biochar is today mostly used as a fertilizer and to improve soil structure. However, there is also research ongoing exploring the use of biochar in concrete or in renders and mortars with a cement-based or lime-based binder [18–22]. Adding biochar to cement or lime could improve the material's environmental impact as biochar functions as a carbon sink [23]. Using biochar in building materials is effectively contributing to carbon capture in the material, thus decreasing the amount of carbon that is released into the atmosphere. In addition, the algae biomass is not returned to the sea thus reducing eutrophication in the Baltic Sea. According to [24] biochar plaster (biochar added to a lime-based binder) has a good moisture storage capacity and can function as a humidity regulator in environments that have occasional peaks in relative humidity. Therefore, biochar was added to the hemp-lime in this study to determine if adding biochar to the hemp-lime would improve its moisture buffering capacity.

Fig. 4. Left: Beach cast seaweed at the southern Swedish coast. Right: Biochar produced from local sea weed.

2 Materials and Methods

The following materials were studied in this paper;

- HL: Hemp-lime (Tradical® Thermo lime and Granngården hemp hurds),
- HL20: Hemp-lime with 20% biochar (20% of the lime binder replaced by seaweed-based biochar. Seaweed provided by Trelleborgs municipality, seaweed pyrolyzed by Skånefrö),
- HL50: Hemp-lime with 50% biochar (50% of the lime binder replaced by seaweed-based biochar),

– RL: Rape straw-lime (Tradical® Thermo lime, and rape straw provided by Halmeko Scandinavia).

The hemp-lime was produced in accordance with instructions provided by the manufacturer's product sheet for lining plaster application with a trowel. Rape straw-lime was produced in a similar way as the hemp-lime in this study, with Tradical® Thermo lime as a binder. For the Tradical® Thermo lime the material quantities for the application Lining with trowel were used. The hemp-lime in this study is thought to be used as an indoor lime plaster used for renovation purposes, in other words, the plaster would most likely be applied by a mason with a trowel on site. Samples were produced with a thickness of approx. 50 mm and a surface area of 150x150 mm. Exact measurements of the surface area as well as exact sample thickness were performed prior to each moisture buffer test (Table 1 and Fig. 5)

Table 1. Material proportions by weight.

Abbreviation	Lime [kg]	Shiv or straw [kg]	Water [kg]	Biochar [kg]
HL	2.70	1.0	4.0	0.0
HL20	2.16	1.0	4.0	0.54
HL50	1.35	1.0	4.0	1.35
RL	2.70	1.0	4.0	0.0

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Fig. 5. Left: Hemp-lime, center: Hemp-lime with 20% biochar, right: Hemp-lime with 50% biochar.

Biochar was produced by Skånefrö AB of beach cast sea weed from the southern Swedish coastline near the city of Trelleborg. The biochar consisted of small lumps, see Fig. 4, and was therefore ground into smaller particles before it was added to the binder mix. Particle size distribution of the ground biochar is shown in Fig. 6.

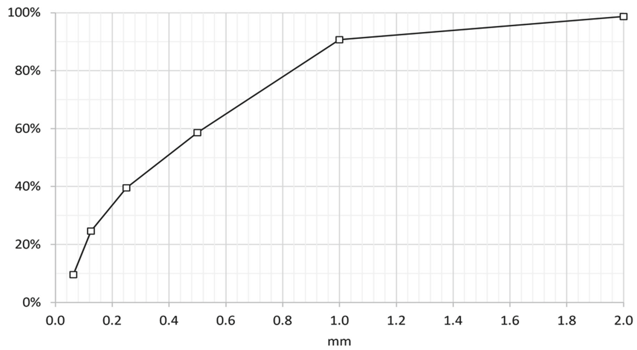

Fig. 6. Particle size distribution of the ground biochar.

2.1 Thermal Properties

Thermal conductivity, thermal diffusivity and specific heat capacity were measured by a Transient Plane Source (TPS) method using a Thermal Constants Analyzer (TPS1500, HotDisk®). After the moisture buffer measurements, specimens were dried in a heating cabinet at 40 °C until mass change was less than 0.01% between three consecutive weighing at 24-h time steps. Drying at this rather low temperature prior to testing thermal properties was done to perform the measurements on a sample that is sufficiently dry so that moisture flows within the material do not interfere with the measurement too much. Drying at a higher temperature might have altered material properties and would not have been representative to actual conditions in a building. The dried samples were placed in plastic bags, and the samples in their plastic bags were placed in plastic containers with a desiccant and a glass lid. Samples were transported to the TPS1500 HotDisk® device inside the plastic containers and remained there for 24 h to acclimatize to the surrounding temperature (21 °C). When performing the measurements, specimens were kept inside the plastic bags, with the sensor on top of the material surface. On top of the sensor, a rigid insulating material with known material characteristics was placed with a weight on top. At least three measurements were performed per sample, three samples per material. Measurements were performed at 2-h intervals with sensor Kapton 8563 (9.868 mm), measurement time 320 s and output power 40 mW.

After the measurements were completed, the samples were returned to the drying cabinet where they were kept at 40 °C. Once all measurements with the TPS1500 HotDisk® device were completed, the samples were dried at 105 °C and moisture content at 40 °C was determined, see Table 3.

2.2 Moisture Buffering

To determine the moisture buffering capacity of the materials in this study, an adaptation of the NORDTEST protocol [25] was used. In the NORDTEST protocol the moisture buffer performance of a room is described as"the ability of the materials within the room to moderate variations in the relative humidity" [25].

Usually, the sorption isotherm is used to define moisture absorption and moisture desorption of a building material. A sorption isotherm for a building material can be determined in a lab situation, waiting for the material to reach equilibrium with its surroundings. However, when a material is used in a building, the material will most likely not reach equilibrium because of fluctuations in temperature and relative humidity. Instead, the material will have a moisture content that fluctuates between its sorption and desorption isotherm. This is why the moisture buffer value of a material could be a more suitable indicator of the moisture absorption and desorption of a material in a shorter time span.

The practical moisture buffer value ($MBV_{practical}$) is defined by [25] as "the amount of water that is transported in or out of a material per open surface area, during a certain period of time, when it is subjected to variations in relative humidity of the surrounding air" [25].

The time period and variations in relative humidity proposed by the NORDTEST protocol are cyclic variations of 8 h of 75%RH followed by 16 h of 33%RH;

$$MBV_{practical} = \frac{\Delta m}{A \cdot \Delta RH}\ [\text{kg}/(\text{m}^2\%\ \text{RH})]\ \ [25]$$

Δm = mass, defined as the average of the weight gain moisture uptake (absorption), and the weight loss during moisture release (desorption) [kg].

ΔRH = the difference in relative humidity between the high RH (8 h of 75% RH) and low RH (16 h of 33%RH) [%].

A = area of the moisture buffering material exposed to the fluctuations in relative humidity [m^2].

As a direct cause of the Covid-19 pandemic access to the building lab was limited during a long period of time. This made it considerably more difficult to perform manual measurements. Therefore, instead a climate test cabinet (CTS C-20/1000) was used to create an environment with cyclic variations of 75%RH for 8 h followed by 33%RH for 16 h. Inside the climate test cabinet three scales (OHAUS Scout with an accuracy of two decimals) were placed that continuously measured the weight of the samples that were suspended underneath the scales.

Also, additional plastic containers were placed beneath the specimens to protect them from too strong air flows inside the climate test cabinet. Air velocity inside the climate test cabinet can influence the moisture buffer value of the material since air velocity has an influence on the surface transfer coefficient. The Nordtest protocol mentions an air velocity interval of 0.10 ± 0.05 m/s [25]. The air velocity inside the climate test cabinet was measured near the surface of each of the three samples and found to be 0.14 ± 0.10 m/s.

Prior to the moisture buffer test, samples were dried; 24 h at 40 °C followed by 24 h at 50 °C followed by drying at 60 °C until equilibrium was reached. Equilibrium was reached when variation in weight was less than 0.01% between three consecutive weighing at 24-h time steps. After drying, the samples were placed in a climate chamber with relative humidity 60 ± 5% and temperature 20 ± 0.5 °C until they reached equilibrium; variation in weight less than 0.01% between three consecutive weighing at 24-h time steps. Before the specimens were subjected to the moisture buffer test inside the climate test cabinet, aluminum tape was applied to all but one surface of the samples. The surface area was measured for each specimen. The surface that was left open would be able to absorb and desorb moisture once inside the climate test cabinet, see Fig. 7.

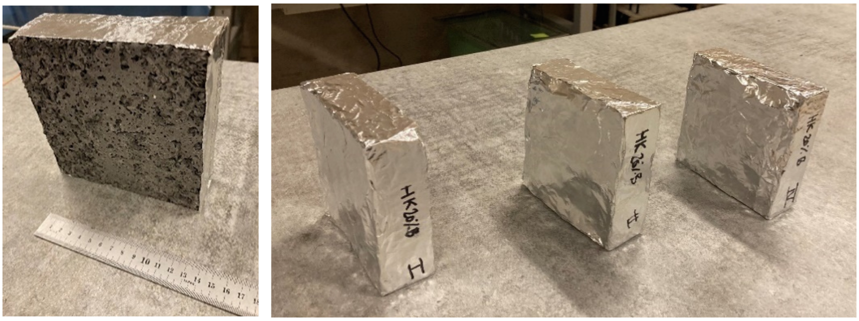

Fig. 7. Examples of specimens sealed with aluminum tape on all but one surface.

Each scale was placed inside a plastic container with a glass lid. Inside the plastic container, desiccant was placed to keep the relative humidity inside the container as stable as possible. However, it was found that the scales anyway were subjected to changes in moisture inside the climate test cabinet. To allow the suspended stirrup to move freely, a small hole was made in the bottom of the plastic container. Air could pass freely through this hole, changing the relative humidity in the scale environment somewhat. The scales were found to react to this change in relative humidity, affecting the measurements. Therefore, a calibration of the scales was performed by weighing steel weights while they underwent the same cyclic variations; 33%RH for 8 h followed by 75%RH for 16 h. A steel weight 500 grammes was weighed by each scale respectively, throughout a minimum of three cycles. These measurements were used to calibrate the data.

Between each cycle, 30 min was required for the climate test cabinet to change from 33%RH to 75%RH or from 75%RH to 33%RH. This time was not included in the 8-h period of 33%RH or in the 16 h period of 75%RH. Thus, a period of 8 h 33%RH was followed by 30 min changeover time. Then a period of 16 h 75%RH, again followed by 30 min to reach 33%RH. This led to a total phase time of 25 h (instead of 24 h as required by the NORDTEST protocol). In order to get a value for MBV that can be compared to other research results, it was important to have a moisture buffer value for 24-h cycles. Therefore, the weight change during these last 30 min of each relative humidity level was disregarded when analyzing the results, see Fig. 11.

Data analysis was performed in MATLAB R2020b. Measurement results were imported in MATLAB. The changes in weight that were registered for the steel weight throughout the cyclic variations were deducted from the measurement results. Measurements for all materials had been made every 15 s. A moving average was calculated for every 80 measurement values. The moving average was then used to calculate the moisture buffer value. Moisture buffer values were calculated both for absorption and desorption. The average moisture buffer value was calculated from a minimum of three relative humidity cycles per material for three specimens per material.

3 Results and Discussion

Dry apparent density of the materials was determined, three samples per material. When adding biochar to the material the overall apparent density decreased, see Table 2.

Table 2. Dry apparent density of material samples. Drying of samples at 60 °C.

Material	Dry apparent density [kg/m^3]	Standard deviation
HL	487.5	25.8
HL20	477.0	7.2
HL50	422.1	33.4
RL	468.0	37.6

3.1 Thermal Properties

Thermal conductivity, thermal diffusivity and specific heat capacity were determined by a Transient Plane Source (TPS) method. The moisture content of the materials at the time of the thermal testing was determined, see Table 3. The moisture content in the hemp-lime specimens with 50% biochar was the highest.

Table 3. Moisture content of material samples prior to thermal test. Dry weight at 105 °C.

Material	Moisture content	Standard deviation
HL	3.12%	0.04%
HL20	3.17%	0.05%
HL50	3.82%	0.09%
RL	3.06%	0.06%

The results from the thermal testing showed that the thermal conductivity of the materials decreased when biochar was added to the specimens. The hemp-lime specimens without biochar had the highest values for thermal conductivity. Rape straw-lime and hemp-lime with 50% biochar had similar values for thermal conductivity, see Fig. 8.

Thermal diffusivity also decreased for the material with biochar, with the specimens of hemp-lime with 50% biochar showing the lowest value for thermal diffusivity. This indicates that a hemp-lime with biochar would allow for a slower heat flow through the material, thus contributing to a more stable indoor climate. The specific heat capacity of the three hemp-lime materials was quite similar, see Fig. 9. Here the rape straw-lime material showed somewhat lower values for specific heat capacity, indicating that less heat is needed to change the temperature of the rape straw-lime, even though the standard deviation was quite high. Overall, the specific heat capacity of the tested materials can be compared to aerated concrete with values 0.4 MJ·m-^{3}K-1 for aerated concrete with density 400 kg·m^{3} and 0.5 MJ·m-^{3}K-1 for aerated concrete with density 500 kg·m^{3} [26].

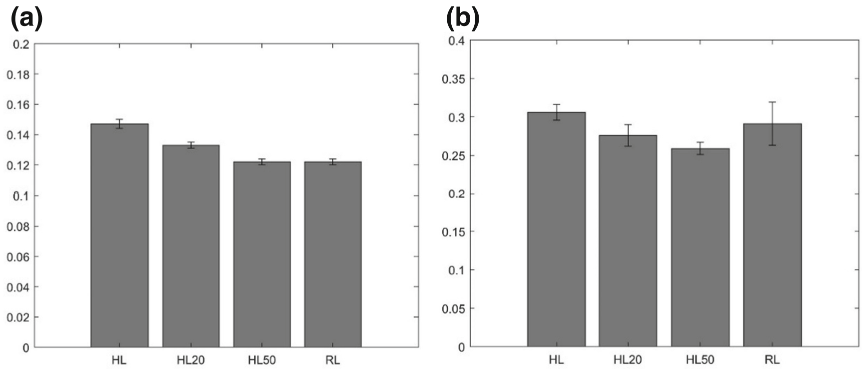

Fig. 8. (a) Thermal conductivity [W·m^{-1}·K^{-1}]. (b) Thermal diffusivity [mm^{2}·s^{-1}].

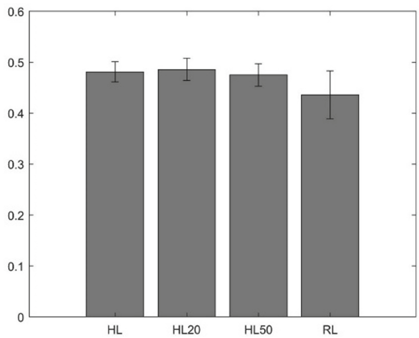

Fig. 9. Specific heat capacity [MJ·m^{-3}K^{-1}]

3.2 Moisture Buffering

Data from the moisture buffer measurements had to be calibrated. Each of the three scales had a different calibration file. This data had to be deducted from the measured raw data.

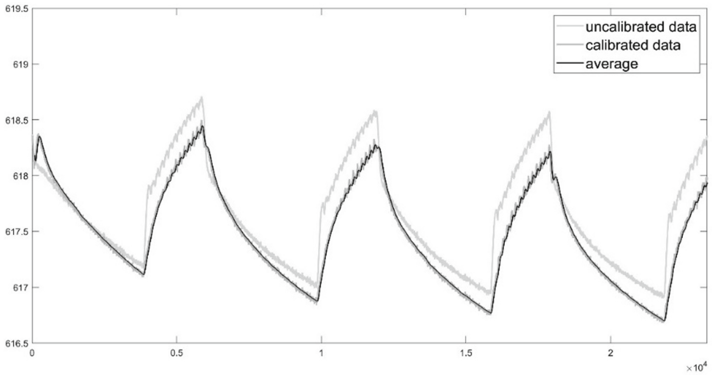

Fig. 10. Weight of one sample of hemp-lime undergoing the moisture buffering regime. Light grey line uncalibrated data, dark grey line calibrated data and black line average data for 80 data points (equivalent of 10 min). The data is shown before calibration and after calibration, taking into account the changes in the scale due to changes in RH.

After calibration, a moving average value was calculated, see the black continuous line in Fig. 10.

Also, half an hour of each relative humidity level had to be excluded as measurements had been made for 8.5 h 75%RH and 16.5 h 33%RH. To allow values to be compared to other $MBV_{practical}$ the data had to be adjusted to 8/16 h intervals, see Fig. 11.

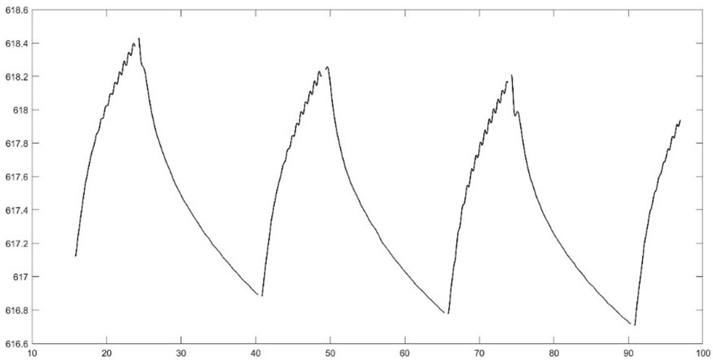

Fig. 11. Weight of one sample of hemp-lime undergoing the moisture buffering regime, excluding 30 min with each change in RH.

According to [22] the level of $MBV_{practical,}$ can be divided into five categories; negligible for values <0.2 g/m^2·%RH, limited 0.2–0.5 g/m^2·%RH, moderate 0.5–1.0 g/m^2·%RH, good 1.0–2.0 g/m^2·%RH and excellent >2.0 g/m^2·%RH.

Results from the moisture buffering measurements showed that the hemp-lime and rape-straw lime materials either have “good” or “excellent” practical moisture buffer values, see Fig. 12.

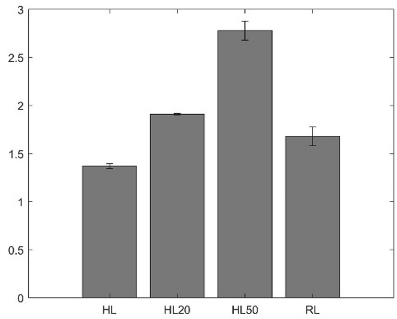

Fig. 12. Average moisture buffer value for all four materials.

Adding biochar to the hemp-lime material increased the moisture buffer value, with an average value of 2.78 $g/m^2 \cdot \%RH$ for hemp-lime with 50% biochar, thus providing *excellent* moisture buffer capacity.

4 Conclusions

Biochar is an interesting material for use in many different applications, one of which could be the use as an additive in building materials, for example in hemp-lime.

Before using biochar in building materials more research is needed. For example, the choice of biomass from which the biochar is produced will have an influence on the final material properties. Biochar based on seaweed will have some marine salts still present which could potentially negatively influence the material in which the biochar is used. Which salts and how much salt is still present in the biochar should be investigated prior to its use in building materials. Biomasses other than seaweed could be a potentially good source for biochar suitable for building.

Adding biochar to the hemp-lime gave a material with lower density, lower thermal conductivity, and lower thermal diffusivity. From a thermal insulation point-of-view it could therefore be beneficial to add biochar to the mix. Regarding moisture buffering, adding biochar increased the practical moisture buffer value, achieving a material with excellent moisture buffer capacity. Adding biochar to the surface finish of historic buildings could therefore contribute to achieving an indoor climate with stable temperature and stable relative humidity.

The rape straw-lime mix used in this study showed material properties similar to those of hemp-lime and could therefore be a valid alternative to hemp-lime in Sweden where hemp cultivation is scarce and rape seed is cultivated in abundance.

Acknowledgements. This research was funded by the Swedish Energy Agency through the *Spara och Bevara* research programme (grant number 50974–1) and the European Union through the project Greater Bio (Grant nr NYPS 20203414) funded by Interreg Öresund-Kattegat-Skagerak (ÖKS). The role of these funding sources was strictly financial.

The laboratory work in this study was performed in cooperation with research engineer Stefan Backe. His help is gratefully acknowledged.

References

1. Thomson, G.: The museum environment, 2. ed. London: Butterworth-Heinemann in association with the International Institute for Conservation of Historic and Artistic Works (1986)
2. Ferreira, C., de Freitas, V.P., Delgado, J.M.P.Q.: The influence of hygroscopic materials on the fluctuation of relative humidity in museums located in historical buildings. Stud. Conserv. **65**(3), 127–141 (2020). https://doi.org/10.1080/00393630.2019.1638666
3. Rahim, M., et al.: Characterization of flax lime and hemp lime concretes: hygric properties and moisture buffer capacity. Energy Build. **88**, 91–99 (2015). https://doi.org/10.1016/j.enbuild.2014.11.043
4. Collet, F., Chamoin, J., Pretot, S., Lanos, C.: Comparison of the hygric behaviour of three hemp concretes. Energy Build. **62**, 294–303 (2013). https://doi.org/10.1016/j.enbuild.2013.03.010
5. Latif, E., Lawrence, M., Shea, A., Walker, P.: Moisture buffer potential of experimental wall assemblies incorporating formulated hemp-lime. Build. Environ. **93**, 199–209 (2015). https://doi.org/10.1016/j.buildenv.2015.07.011
6. Strandberg-de Bruijn, P.B., Balksten, K.: Energy and moisture in historic masonry walls retrofitted with hemp-lime.In: IOP Conference Series: Materials Science and Engineering, vol. 660, p. 12070 (2019). https://doi.org/10.1088/1757-899x/660/1/012070
7. Strandberg-de Bruijn, P., Donarelli, A., Balksten, K.: Full-scale studies of improving energy performance by renovating historic Swedish timber buildings with hemp-lime. Appl. Sci. **9**(12), 2484 (2019). https://doi.org/10.3390/app9122484
8. Arnaud, L., Gourlay, E.: Experimental study of parameters influencing mechanical properties of hemp concretes. Constr. Build. Mater. **28**(1), 50–56 (2012)
9. Källgren, V.: Ljudmiljö i kulturmiljö - hampakalks akustiska egenskaper och tillämpbarhet i kulturhistoriskt värdefulla byggnader. Uppsala Universitet Campus Gotland (2017)
10. Persson, J., Edbladh, J.: Hampakalk -En jämförelsestudie med avseende på brandegenskaper. Lunds Tekniska Högskola, (2018)
11. Swedish Board of Agriculture, "Hemp cultivation," 2022
12. Swedish Board of Agriculture, "Jordbruksmarkens användning 2022. Slutlig statistik (2022). https://jordbruksverket.se/om-jordbruksverket/jordbruksverkets-officiella-statistik/jordbruksverkets-statistikrapporter/statistik/2022-10-20-jordbruksmarkens-anvandning-2022.-slutlig-statistik
13. Holstmark, K.: Hampa i ekologisk odling, Jönköping (2006)
14. Prade, T., Björnsson, L., Lantz, M., Ahlgren, S.: Can domestic production of iLUC-free feedstock from arable land supply Sweden's future demand for biofuels? J. Land Use Sci. **12**(6), 407–441 (2017). https://doi.org/10.1080/1747423X.2017.1398280
15. Peñaloza, D., Erlandsson, M., Falk, A.: Exploring the climate impact effects of increased use of bio-based materials in buildings. Constr. Build. Mater. **125**, 219–226 (2016). https://doi.org/10.1016/j.conbuildmat.2016.08.041
16. Risen, E., Tatarchenko, O., Grondahl, F., Malmstrom, M.E.: Harvesting of drifting filamentous macroalgae in the Baltic Sea: an energy assessment. J. Renew. Sustain. Energy, **6**(1), 013116 (2014).https://doi.org/10.1063/1.4862783
17. Paulsson, M.: Sammanfattande slutrapport för projektet Rest till Bäst (Steg 2) (2020). https://biokol.org/publikationer/pdf/sammanfattande-slutrapport-steg-2
18. Choi, W.C., Do Yun, H., Lee, J.Y.: Mechanical properties of mortar containing bio-char from pyrolysis." J. Korea Inst. Struct. Maint. Insp. **16**(3), 67–74 (2012)
19. Cuthbertson, D., Berardi, U., Briens, C., Berruti, F.: Biochar from residual biomass as a concrete filler for improved thermal and acoustic properties. Biomass Bioenerg. **120**, 77–83 (2019). https://doi.org/10.1016/j.biombioe.2018.11.007

20. Suarez-Riera, D., Restuccia, L., Ferro, G.A.: The use of Biochar to reduce the carbon footprint of cement-based materials. Procedia Struct. Integr. **26**, 199–210 (2020). https://doi.org/10.1016/j.prostr.2020.06.023
21. Tan, K., Pang, X., Qin, Y., Wang, J.: Properties of cement mortar containing pulverized biochar pyrolyzed at different temperatures. Constr. Build. Mater. **263**, 120616 (2020). https://doi.org/10.1016/j.conbuildmat.2020.120616
22. Maljaee, H., Madadi, R., Paiva, H., Tarelho, L., Ferreira, V.M.: Incorporation of biochar in cementitious materials: a roadmap of biochar selection. Constr. Build. Mater. **283**, 122757 (2021). https://doi.org/10.1016/j.conbuildmat.2021.122757
23. Gupta, S., Kua, H.W.: Factors determining the potential of biochar as a carbon capturing and sequestering construction material: critical review. J. Mater. Civ. Eng. **29**(9), 0401708 (2017). https://doi.org/10.1061/(ASCE)MT.1943-5533. 0001924
24. Abi Khaled, F., Enriquez, P.: Biochar addition to a lime-hemp insulating plaster, Politecnico di Torino, Italy (2020)
25. Rode, C., et al.: Moisture Buffering of Building Materials. Kongens Lyngby (2005)
26. Burström, P.G.: Byggnadsmaterial - Tillverkning, egenskaper och användning, _3rd ed. Lund: Studentlitteratur AB, Lund, Sweden (2021)