Influence of production on hemp concrete hygrothermal properties: sorption, water vapour permeability and water absorption

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Abstract. Hemp concrete is considered to be a carbon negative material. Hemp absorbs CO₂ during the growth and lime needs CO₂ for carbonation. The material, which has good thermal insulation properties, is used as a non-bearing wall material or plaster. For such use the hygrothermal properties of a material must be well known especially when indoor insulation is in focus. In the current study hemp concrete produced in two different ways was in focus and following the hygrothermal properties of hemp concrete as a building material were studied: water absorption (EN 1015-18), water vapour sorption (EN 12571), water vapour permeability (EN 12572) and thermal conductivity (EN 12667). The results of the study can be used in hygrothermal calculations and modelling.

1. Introduction

Construction sector produces a remarkable amount of greenhouse gases. Mineral materials are especially unpopular for several reasons, mainly because mineral resources are being depleted and CO₂ is released during the production process. Therefore, building materials with low embodied carbon, possibly with high carbon storage are helpful [1]. Bio-based materials incorporating biomasses like wood, fibres and plants are of interest [2].

Pervaiz and Sain studied the carbon storage potential of hemp in natural fibre in composite with polypropylene matrix and 325 kg of carbon storage was estimated in the biomass of hemp fibres of metric ton at case of 65% of fibre content [3]. The LCA of hempcrete was carried out by Arrigoni and others [4]. Carbonation was studied by X-ray Powder Diffraction and it was found that after 240 days only the outer (0-2 cm) layer of a 25 cm block was carbonated (about 50% of binder mass) and CO₂ captured was estimated to be 7 g per kg of binder for the sample containing just dolomite lime and 12 g per kg for binder containing also cement. Lagerblad introduced a equation to calculate life-time CO₂ uptake [5]. Cultrone et al [6] found out that by using forced carbonation (CO₂) 90% carbonation can be achieved within 8 days, with 6% weight gain.

Walker and Pavia [7] focused on the variations of binder while studying the hygrothermal properties of hemp lime. Water vapour diffusion resistance was estimated as µ=5.42-5.71 and water absorption coefficient C=2.65-3.37 kg/(m²h⁰.⁵). Tran Le et al [8] found a positive connection between heating demand, ventilation, and moisture buffering – 45% reduction of energy consumption can be reached.
The thermal properties of hemp lime were studied by Walker and Pavia, and for material with 531-627 kg/m³ density thermal conductivity was found as 0.117-0.138 W/mK being in well accordance with the equation derived by Cerezo [7].

If testing hemp concrete is planned, it is not easy to estimate what type of material we have: precast blocks, massive walls or monolite, concrete with wood chips, insulation, or mortar. Several approaches have been presented by researchers. Sicakova et al [9] tested building mixes containing different fine particles suitable for concrete and mortar for water absorption according to EN 1015-18. It seems most suitable for authors also because specimens size and shape (40×40×160) seem to be optimal. Other tests were performed according to the standards suitable for building materials generally. As the authors had earlier experience with the sorption of non-carbonated lime specimens, this time carbonation was forced for some specimens [10].

2. Materials and methods

2.1. The preparation of specimens. Carbonation process

The recipes of hemp concrete mixture with large hemp shiv (coarse) and small one (fine) were the following: 4 litres of hemp strands, 1.5 and 1 litres of water and 1 litre of lime paste. The large shivs had fraction with about 15-30 mm length and small one with 10-15 mm. The production of hemp concrete mixes is described in more detail by Pau et.al [11]. The material can be used as an internal plaster or massive wall, Pau et al [11] studied possibilities to use that as an internal insulation. Two types of specimens were prepared (disks d=103 mm, height 25 mm and prisms 40×40×160 mm). At first, the specimens were stored at 10 °C and RH=70-80% for 3 months, after that for three months (summer) at a pavilion protected from the sun. After 6 months the specimens arrived at a well-ventilated office room and at arrival they were tested with phenolphthalein (1%) (Figure 1).

![Six months old specimens before testing and carbonation process.](image)

Since September 2020 to January 2021 the specimens were stored in a well-ventilated office (laboratory) room. At the start point the test specimens had not been carbonated yet. Non-carbonated in the current study means that the specimens were stored in a well-ventilated room. Randomly monitored CO₂ levels varied between 400 to 700 ppm. Two mixtures (coarse and fine) were tested and divided into two groups: carbonated and non-carbonated materials and four test groups in total: coarse carbonated, coarse, fine carbonated, and fine. To force carbonation the specimens were put into a tight 25 l plastic wine bucket (because of its air tightness) and after weighing 10 l/min of CO₂ was added regularly for one minute once a day. Before next weighing CO₂ was monitored and that exceeded 5000 ppm (upper value for measuring device KIMO AMI 300, sensor SCO2TH). For water vapour access some water was put on the bottom of bucket. During the test RH increased every day – it started at RH=57% and reached RH=87% after 11 days. As the best RH value for carbonation is between RH=50-80% [12], carbonation monitoring was finished after reaching RH=87%.

The other group passed monitoring in a climate chamber to find out whether the specimens were able to stabilize weight. The specimens were marked according to their treatment (1 - number in the group, F - treated with Phenolphthalein, C – carbonated). Weight gain was recorded in both cases, but as the specimens (especially coarse) decomposed easily, the results are not presented hereby. After
carbonation, the specimens were tested with phenolphthalein again and no mark of pink colour was detected (Figure 2). The specimens which were kept only in the climate chamber still turned pink (Figure 3). Dry density data is presented in Table 1. There is some tendency that the density of carbonated coarse specimens is higher than for that of non-carbonated coarse specimens.

**Table 1.** Dry density of specimens.

| Specimen group     | Disks | Prisms |
|--------------------|-------|--------|
| Fine               | 361   | 445    |
| Coarse             | 231   | 277    |
| Fine carbonated    | 362   | 447    |
| Coarse carbonated  | 245   | 286    |

2.2. Equipment

The main equipment used to carry out the tests was: the climate chamber RUMED 4101 affording temperature 0-60°C with ± 0.5 °C accuracy and RH 20-95% with ± 2-3% accuracy and digital balance Kern PLT 1200-3A 0.005-1200 g with 0.001 g accuracy. For thermal conductivity Fox 200 Heat Flow Meter (standard ASTM C518-4) was used. Also, supporting equipment was used: air temperature and RH loggers Hobo UX100-0023, air temperature, RH,
and CO₂ loggers Extech EXCO210 and KIMO AMI 300 with sensor SCO2TH, drying oven Memmert UFB-500.

2.3. Tests for hygrothermal properties

2.3.1. Water vapour permeability. Water vapour permeability was tested according to ISO 12572 [13] with five specimens for each group. The climate chamber method was used, and type C was chosen (RH=50/93%). Weighing was performed regularly with a 12 h interval Figure 4. Environmental data was monitored in the laboratory room, and air temperature and RH in the climate chamber also.

2.3.2. Water absorption was tested according to EN 1015-18 [14]. Before testing the specimens were dried according to ISO 12570 [15]. Three specimens from each group were split into two equal parts. Waterproofing material Fibergum was used to seal the long faces.

2.3.3. Sorption properties were tested according to ISO 12571 [16] and dried according to ISO 12570, four specimens from each group. Environmental data was monitored in the laboratory room, also air temperature and RH in the climate chamber.

2.4. Thermal conductivity
Thermal conductivity was estimated following the principle of EN 12667 [17]. The specimens were conditioned at 20 ± 3 °C air temperature and RH=40 ± 10% for a month. The test was carried out at temperature of 10 °C whereas the temperature difference between the plates was 5 °C. There were some deviations from standard methodology. 30 mm (200*200 mm) thickness could not be afforded because of structure of material and thickness of 50 mm was used. Also, necessary smoothness of surfaces was not applicable because of material structure.

3. Results and discussion

3.1. Water vapour permeability
The fine specimens with small shivs had quite smooth surfaces while the coarse specimens were rather unsmooth. Also, the 2.5 cm thickness of disks was quite small. Therefore, the data of the coarse group had a large variance. The non-carbonated specimens presented similar values (µ = 3.8 for fine and µ=4.0 for coarse) despite the production type (Table 2). The highest value (µ=4.4) was presented by the carbonated coarse and the lowest (µ=3.5) the fine carbonated material. It is remarkable as the fine carbonated material had the highest dry density.

Anyway, the differences were small, and all findings can be presented as one result µ=3-5 regardless of shiv size or carbonation. The results are comparable with those found by Walker and Pavia (µ=5.42-5.71, at density 531-627 kg m⁻³). Environment in the laboratory room was monitored – average air temperature was 20.0 (16.9-24.5)°C and RH as 20.1 (13.3-27.9)% was recorded.
Table 2. Water vapour resistance factor $\mu$ and water vapour permeability $\delta \cdot 10^{-11}$ kgm$^{-1}$s$^{-1}$Pa$^{-1}$.

| Specimen group          | $\mu$ | $\delta \cdot 10^{-11}$ |
|------------------------|-------|-------------------------|
| Fine                   | 3.8   | 5.1                     |
| Coarse                 | 4.0   | 5.0                     |
| Fine carbonated        | 3.5   | 5.5                     |
| Coarse carbonated      | 4.4   | 4.4                     |

3.2. Water absorption

The specimens (prisms) were weighed at dry condition after 10 and 90 minutes, and 24 hours following the start of immersion. The broken faces were extremely unsmooth; 10 mm immersion depth was followed. Surface absorption coefficients after 90-10 minutes were received as $1.41 \cdot 1.90$ kgm$^{-2}$min$^{-0.5}$ (Table 3). At 24 hours weighing it was fixed that the specimens had been saturated. The time of saturation was not recorded (Figure 5). Similar values were received with fine ($A_w = 1.86$ and $1.9$ kgm$^{-2}$min$^{-0.5}$) and coarse material ($A_w = 1.41$ and $1.45$ kgm$^{-2}$min$^{-0.5}$). Carbonation did not influence water absorption properties.

Figure 5. Water absorption test.

Table 3. Water absorption coefficient $A_w$ (kgm$^{-2}$ min$^{-0.5}$) and saturated water content $WC$ (kgm$^{-3}$) of specimens.

| Specimen group          | $A_w$ | WC  |
|------------------------|-------|-----|
| Fine                   | 1.86  | 208 |
| Coarse                 | 1.41  | 186 |
| Fine carbonated        | 1.9   | 217 |
| Coarse carbonated      | 1.45  | 195 |

3.3. Water vapour sorption

For sorption, the measuring points were estimated as RH=30, 50, 75 and 95% (Figure 6). The coarse specimens (at RH=50%, MC=4.3%) and especially carbonated coarse specimens showed the highest values (at RH=50%, MC=4.6%). The fine specimens presented only MC= 3.5-3.6%.
Figure 6. Sorption curves for all test materials

At critical level for building materials (RH=75%) MC=7.0% for the coarse carbonated and MC=6.6% for the coarse material. The fine material presented MC=5.4 and 5.3% accordingly. At low RH conditions (RH=30%) MC=2.4-3.1%. At highest possible level offered by climate chamber (RH=95%) fine and both coarse specimens presented similar values (MC=14.9-16.0%), while fine carbonated had clearly lower value (MC=12.2%). Desorption values were 2-3% higher for levels RH=30%. RH=50% and RH=75%. The highest hysteresis was presented by fine specimens (ΔMC=3% average).

The weighing process showed that the weight gain was received within 24 hours and after that only stabilisation condition (weight gain less 0.1% within the three last weighing) was fulfilled. As the densities were different, the moisture content per cubic metre was calculated for the fine specimens at RH=75% as 5.4%*361=19.5 kg/m$^3$ and the carbonated coarse 7.0% *245=17.1 kg/m$^3$ which were quite similar. At RH=50%, the results were 12.6 and 11.3 kg/m$^3$. The clay plaster with hemp addition (1357 kg/m$^3$) and MC=1.3% and RH=50% had 17.6 kg/m$^3$ moisture content [18]. The paper plaster had MC=10.5-14% at RH=50% [19]. The maximum moisture content per cubic metre at RH=95% was obtained as 55.6 kg/m$^3$ for fine and 37.1 kg/m$^3$ for coarse specimens.

3.4. Thermal conductivity
Thermal conductivity is highly dependent on density. Cerezco derived Equation 1 [7] for the calculation of thermal conductivity $\lambda$ (W/m$^1$K$^{-1}$) dependent on density $\gamma$ (kg/m$^3$):

$$\lambda = 0.0002 * \gamma + 0.0194$$  \hspace{1cm} (1)

In our study several densities were received depending on the preparation of the specimens, and according to that thermal conductivity (calculated) could be expected to be from $\lambda$=0.066 W/m$^1$K$^{-1}$ for 230 kg/m$^3$ density to $\lambda$=0.109 W/m$^1$K$^{-1}$ for 447 kg/m$^3$ density.

Also, thermal conductivity was estimated by testing and results were 0.095 W/(mK) for coarse material (295 kg/m$^3$, MC=4.1%) and 0.084 W/(mK) for fine material (318 kg/m$^3$, MC=6.2%). The summarised results can be seen in Figure 7. The calculated and measured values were in very good accordance for fine material but some difference could be found with coarse material.

Figure 7. Thermal conductivity of specimens: blue dots – calculated, red dots - measured.
That could be because of the problems connected with cutting the specimens as is it almost impossible to ensure smooth surfaces especially for coarse material. Even the estimation of density is complicated. It can be said that the density of hemp concrete can be very different and so the thermal conductivity varies.

3.5. The results of the tests in practical calculations

Every producer should be encouraged to find out the actual properties of their production. The authors had an experience with clay plaster where sorption properties differed up to 20 times [18]. The data gathered from this study were water vapour permeability, water absorption properties and water vapour sorption. Thermal conductivity was calculated on the basis of density and controlled with testing. Water vapour permeability and thermal conductivity are part of a simple 1D diffusion calculation.

Probably the greatest effect from usage of hemp concrete will be received if indoor insulation is planned because of its good sorption properties and thermal conductivity. If hemp concrete is used for indoor insulation with 10 cm thickness (for example) and its water vapour diffusion coefficient is $\mu=3.5$, it indicates the probability of condensation problems as $S_w=0.3-0.4$ m. It was found that at RH=50% the moisture content per cubic metre was 11.3-12.6 kgm$^{-3}$ and at RH=75% 17.1-19.5 kgm$^{-3}$.

Good sorption properties indicate good moisture buffering properties which enable to reduce the peaks of indoor RH and therefore possible moisture excess. At 10 cm thickness and 50-75% RH fluctuation water vapour adsorbed could be 590-690 gm$^2$ making the layer a remarkable reservoir.

4. Conclusions

Hemp concrete is a material with good hygrothermal properties - water vapour resistance factor $\mu=3.5-4.4$ – if material with high water vapour permeability and sorption properties is needed. The differences are small and can be also presented as one result $\mu=3.5$ regardless of shiv size or carbonation. The tests should be repeated with a material with higher density.

Water absorption coefficient $A_w=1.41-1.90$ kgm$^{-2}$min$^{-0.5}$ and depends only on the production i.e., shiv size. The results of the sorption test show that coarse material performs higher MC, but if calculated as moisture content per cubic metre, the results are similar - 17.1-19.5 kgm$^{-3}$ at RH=75%.

For hygrothermal calculations detailed data is necessary and the authors encourage each producer to test their material and provide designers with the information. Both shiv type and carbonation seem to have moderate influence on hygroscopic properties like water vapour permeability and sorption. Water absorption is influenced only by the production method (recipe) and shiv size.

Carbonation was studied in a very simple way using phenolphtalein and measuring weight gain. To evaluate the effect of CO$_2$ uptake as a tool to reduce CO$_2$ emission or ventilation, the rate must be studied further. Carbonation process goes on for a long period of time, even for centuries.

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