Binder Formulation and Properties of Hemp Concrete

Mathieu Bendouma, Philippe Fortin, Daniel Perraton,
and Claudiane Ouellet-Plamondon(✉)

École de Technologie Supérieure of Montreal, Montreal, QC H3C 1K3, Canada
Claudiane.ouellet-plamondon@etsmtl.ca

Abstract. The building sector is one of the largest consumers of energy and emitters of greenhouse gases (GHG). The problems linked to climate change push us to design buildings that are more respectful of the environment, whether during the design stage, the life span, or the end of life of the works. The question then arises as to the use of insulating materials of petrochemical and mineral origin, non-renewable. To fight against environmental problems, it is thus necessary to develop new materials that are more eco-responsible and have less impact on the environment. In this sense, hemp concrete is of great interest in the scientific literature. The objective of this research is to determine the feasibility of designing hemp concrete by limiting the addition of hydraulic binder, not available in Canada which promotes GHG emissions (because of transportation) and adding materials available in North America. By combining it with other structural materials, such as OSB, it could replace gypsum board, which is widely used in Canada but often buried instead of recycled. This work will focus on the thermal and hydric properties of hemp concrete developed with metakaolin, to substitute hydraulic lime.

Keywords: Hemp · concrete · thermal conductivity · moisture buffering value

1 Problematic

Hemp concrete has a good thermal conductivity (λ) compared to other building materials such as oriented strand board or gypsum plasterboard. The order of magnitude of the thermal conductivity of this material is around 0.10 W/m/K in dry state, but can be affected by parameters such as its density, temperature or water content [1–4]. Literature on hemp concrete underlined that the mass proportions between the binder and the plant particles also affect the porosity, and thus density, thermal, and hydric properties. Different density for this material makes it adaptable: a low-density hemp concrete can be used for attic or wall insulation, inversely a high-density hemp concrete has better mechanical properties and makes it suitable for floor slabs or insulating wall coatings. This article focus on hemp concrete for thermal insulation. The goal is to develop a mixture without hydraulic binders to lower the embodied carbon of the material.

Most developed hemp concretes are based on hydraulic binders, which are largely available in Europe, for example, but are not locally accessible in Canada. Importing

S. Amziane et al. (Eds.): ICBBM 2023, RILEM Bookseries 45, pp. 442–449, 2023.
https://doi.org/10.1007/978-3-031-33465-8_34

hydraulic binders for the manufacture of hemp concrete would penalize the carbon footprint of this material, while it is one of its major benefits. In Canada hydrated lime is available to develop binders for hemp concrete. This type of lime sets by carbonation, and, at a young age, a proportion of the hydrated lime is not carbonated which does not allow to obtain the mix's cohesion. It is possible to address this challenge with the introduction of pozzolans or hydraulic materials (i.e., cements, natural cement and hydraulic limes with hydrated lime). In order to develop a viable solution for the manufacture of low carbon hemp concrete, it is then necessary to develop a formulation of local binder, adapted to Canada.

Metakaolin, a competitive pozzolan, is a potential candidate to ensure concrete cohesion and is available in North America. In order to optimize the curing of hemp concrete, it is necessary to understand the behaviour of the lime-metakaolin type mixture. This knowledge allows a better comprehension of the impact of introducing metakaolin on the thermal and hydric properties of hemp plant-based concretes. In this work, a thermal and hydric characterization of hemp concrete, manufactured in the laboratory with metakaolin, is presented and compared to the literature and conventional formulation. Other properties, such as mechanical performances of the samples can be found in the work of Fortin and are outside the scope of this article [5].

2 Materials and Method

2.1 Material

Hemp shive particles are harvested in Quebec in the Saguenay-Lac-Saint-Jean region. The hemp cultivar used is USO31 was provided by Agrofibre in Lavaltrie, Quebec, with a length between 180 and 220 cm. The plant was defibred before final bagging of 15 kg packed hemp shives. Table 1 presents the composition of the USO31 hemp fiber variety, and was taken from the literature [6]. The hemp has a bulk density of 125.2 kg/m^3 $\pm$ 2.9 kg/m^3 and an absolute density of 1336 kg/m^3 ($\pm$0.206%).

Table 1. Chemical composition of USO31 hemp fiber [6].

	Cellulose (m%)	Hemicelluloses (m%)	Pectin (m%)	Lignin (m%)
USO31	64–71	4–6	6–10	3–8

In North America, hydraulic lime is mainly accessible by imports from Europe. In this study, and for comparison purposes, a natural hydraulic lime from the company Secil, in Portugal (NHL 3.5) is used. The nomenclature "3.5" indicates that a mortar made with this lime will have a minimum strength of 3.5 MPa, according to the manufacturer's prescribed procedures. The hydraulic and carbonatation reactions by this type of lime allow plant concrete in a young age to attain that minimum mechanical resistance.

In Canada, the company Graymont can provide hydrated lime (CHX, *Graymont's High Calcium Lime)* which makes it a local available product, limiting the transportation and associated environmental impacts of this resource, necessary for the manufacture of hemp-based concrete.

Some distributors can supply metakaolin in eastern North America, among them the company *Poraver* is located in Ontario, Canada. The company's commercial product is called *Metapor* and is generally used nowadays as a supplementary cementing material in the manufacture of reinforced and unreinforced cement concrete elements. *Metapor* is mainly composed of an impure metakaolin and an addition of expanded recycled glass. The chemical composition of *Metapor* can be found in recent literature [7]. Theoretical calculation of the proportion of metakaolin (MK) and hydrated lime (CHX) for a total consumption of hydrated lime to occur during the process is based on Eq. (1), based on the work of Murat, 1983 [8].

$$\mathrm{AS_2 + 6CH + 9H_2O \rightarrow C_4AH_{13} + 2CSH} \tag{1}$$

This calculation of the proportion of meta kaolinite (AS_2) constituents based on their molar mass are $Al_2O_3/AS_2 = 0.45899$ and $2SiO_2/AS_2 = 0.54101$, a detail can be found in Table 2.

Table 2. Calculation of stoichiometric ratios to determine the proportion of metakaolinite.

Molar masses of chemical elements:		
$H = 1.008g$	$O = 16.0g$	$Al = 26.98g$
$Si = 28.09g$	$Ca = 40.08g$	
Molar masses of constituents:		
$Al_2O_3 = 2 \cdot Al + 3 \cdot O = 101.96g$	$SiO_2 = Si + 2 \cdot O = 60.09g$	
$AS_2 = Al_2O_3 + 2 \cdot SiO_2 = 222.14g$		
Stoichiometric ratios:		
$\frac{Al_2O_3}{AS_2} = 0.45899$	$\frac{2 \cdot SiO_2}{AS_2} = 0.54101$	

We can note that $CH = Ca(OH)_2 = Ca + 2 \cdot (O + H) = 74.096g$, whose proportion in CaO is noted as $\%CaO = \frac{Ca+O}{Ca(OH)_2} = 0.757$.

According to the equation of Murat, 1983, the optimized proportion to totality consume the free hydrated lime is close to a 50%/50% ratio. Precisely, 54.8% calcium hydrated lime (CHX) and 45.2% metakaolin (MK). A summary of the binders used in this study is presented in Table 3.

Table 3. Binder used for the formulation of hemp concrete samples.

	MK-45	NHL
Hydrated lime (CHX)	54,8%wt	–
Metakaolin (MK)	45,2%wt	–
Natural hydraulic lime (NHL)	–	100%wt

For the hydric characterization, both formulations are studied, but for the measurement of thermal conductivity, only the formulation based on hydrated lime and metakaolin is considered. The formulation of the studied hemp concrete samples (MK-45) is presented in Table 4.

Table 4. Constituents for the formulation of hemp concrete samples submitted to thermal conductivity tests.

	MK-45
Dry hemp shives (kg)	1
Dry binder (kg)	1,5
Water (kg)	2,5
Dry density (kg/m^3)	326 ± 4

2.2 Method

2.2.1 Thermal Characterization

The hemp concrete is a heterogeneous material which does not allow a measurement with transient or modified transient plane source (TPS/MTPS) available in the laboratory. The thermal conductivity was thus determined with a needle probe and the Transient Line Source method (TLS, Fig. 1), with C-Therm trident, in accordance with ASTM D5334 and ASTM D5930 [9–11]. The sample was drilled with small holes, in different orientations, corresponding to the diameter of the probe and a series of 6 measurements is done. The thermal conductivity is determined using the temperature rise, which varies linearly with the logarithm of time, according to the Eq. (2). The procedure has an associated uncertainty of ± 3% + 0.02 W.m^{-1}.K^{-1} at 20 °C.

$$\lambda = \frac{C.q}{4.\pi.L.\Delta T}.\ln\left(\frac{t2}{t1}\right) \tag{2}$$

With:

- C a calibration factor,
- q the heat flux,

- L the length of the probe,
- ΔT the temperature, and
- t the time.

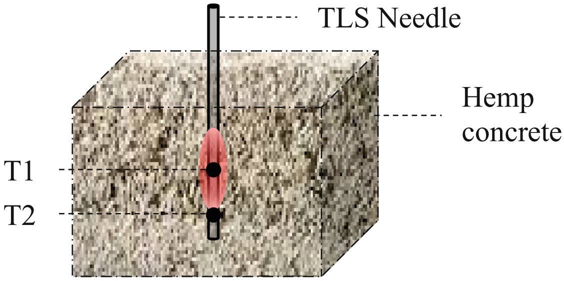

Fig. 1. C-Therm (left) and TLS needle principle (right).

2.2.2 Hydric Behaviour

In order to evaluate the moisture buffering value (MBV) of the samples, the NORDTEST method is used [12]. This method consists of evaluating the moisture absorption and desorption of samples through humidity cycles. The samples are sealed on every surface, except one (with a surface area of at least 0.01 m^2) which is exposed to the controlled environment. Before the tests, the sample are conditioned, and their mass are measured with a balance (with a precision of ±0.01 g). The samples are then submitted to successive high and low humidity cycles, at ambient temperature (23 ± 2 °C). Between each cycle, the mass of the samples is measured and moisture buffering value can be calculated with Eq. (3).

$$MBV = \frac{\Delta m}{A \cdot (RH_{high} - RH_{low})} \tag{3}$$

With:

- m the weight of the sample,
- *A* the exposed surface,
- RH_{high} and RH_{low} are respectively the high and low relative humidity of the cycle.

The velocity and the air film above the samples are neglected and may have an impact on the actual moisture content of the material. The humidity cycles are performed in a commercial *Thermotron* environmental chamber (Fig. 2).

Fig. 2. Moisture Buffering Value Test in Thermotron environmental chamber.

3 Results

3.1 Thermal Conductivity

Thermal conductivity measurements led to values between 0.097 and 0.105 W/m/K for hemp concrete manufactured with metakaolin and a mean of 0.102 $\pm$ 0.004 W/m/K. It corresponds to the measured values of hemp concrete in literature for this material [13], which underline that the thermal performance is not impacted by the introduction of metakaolin. With respect to commonly used mixes, this mix is adapted and confirms the observations of the literature [1, 2]. Furthermore, the impact of introducing metakaolin in the mix, leads to similar observations of Walker and Pavía, as no major impact is observed [14]. As already mentioned, in the case of hemp concrete, thermal conductivity can be dependent on several parameters, other tests would allow determining fiber orientation and compaction impacts. As an example, Zerrouki et al. measured thermal conductivity between 0.062 and 0.125 W/m/K with the consideration of these parameters [15]. The measurement probe was introduced in different orientations, however low standard deviations were calculated (around 4%), which remains relatively low as it would have been expected.

3.2 Moisture Buffering Value

Figure 3 shows the results obtained from the MBV measurements, for the two binders under study (MK-45 and NHL). The calculated averages for the last three moisture cycles (8 to 10), are in the order of 2.64 and 2.90 g.m^{-2}.%RH^{-1} for the hemp concretes formulated with the metakaolin (MK) and the hydraulic binder respectively (NHL). The values obtained for the metakaolin-based sample are slightly lower. However both formulations can be qualified as excellent hydric regulators. These results obtained for this material corroborate with Latif et al. (2015) who attempted the test also on a hemp plant concrete rich in hydrated lime. Thus, the binder formulated with metakaolin seems to be a very good alternative for the manufacture of hemp concrete with a low carbon footprint in Canada.

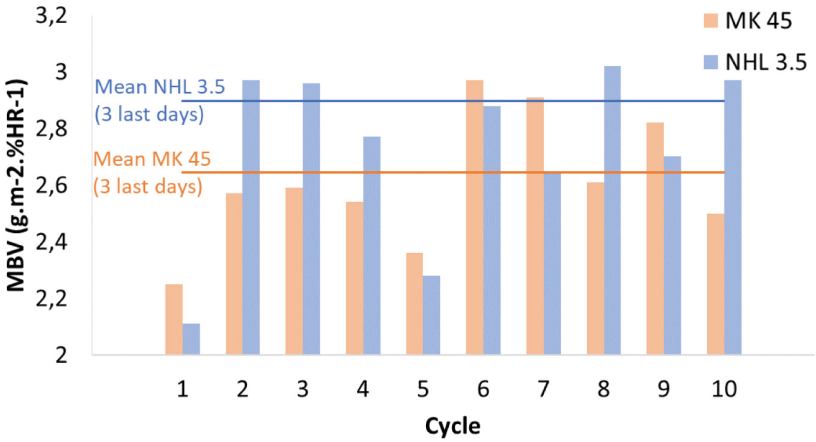

Fig. 3. Moisture Buffering Value measured through each cycle for hemp concrete with NHL and MW

4 Conclusion

The important challenge of this work was to develop a formulation of local binder to replace hydraulic lime. In this study, the thermal conductivity and the moisture buffering values of different samples of hemp concrete were studied. The thermal conductivity of the manufactured hemp concrete samples with metakaolin was in the same range as other hemp concrete presented in the literature. Considering the hydric performance of the formulation, the samples manufactured with metakaolin were a bit less performant as hemp concrete produced with conventional hydraulic binder. The manufactured hemp concrete formulated with a local binder is adapted for the building sector.

References

1. Barbhuiya, S., Das, B.B.: A comprehensive review on the use of hemp in concrete. Constr. Build. Mater. **341**, 127857 (2022). https://doi.org/10.1016/j.conbuildmat.2022.127857
2. Nguyen, T.T., Picandet, V., Carre, P., Lecompte, T., Amziane, S., Baley, C.: Effect of compaction on mechanical and thermal properties of hemp concrete. Eur. J. Environ. Civil Eng. **14**(5), 545–560 (2011). https://doi.org/10.1080/19648189.2010.9693246

3. Arnaud, L., Cérézo, V.: Qualification physique des matériaux de construction à base de chanvre. CNRS, Lyon, Rapport final de recherche 0711462 (2001)
4. Evrard, A., De Herde, A.: Bioclimatic envelopes made of lime and hemp concrete. In: Présenté à CISBAT 2005 - Renewables in a Changing Climate - Innovation in Building Envelopes and Environmental Systems (2005). https://dial.uclouvain.be/pr/boreal/object/boreal:73818
5. Fortin, P.: Formulation d'un liant pouzzolanique pour la confection d'un béton végétal hygroscopique. École de Technologie Supérieure, Montréal, Mémoire en Génie de la Construction (M. Sc. A.) (2022)
6. Mazian, B.: Approche intégrée du procédé de rouissage des fibres de chanvre : Vers une amélioration de la qualité des intrants pour la fabrication des matériaux biocomposites. phdthesis, IMT - MINES ALES - IMT - Mines Alès Ecole Mines – Télécom (2018). Consulté le 15 novembre 2022. https://tel.archives-ouvertes.fr/tel-03019451
7. Brylewska, K., Rożek, P., Król, M., Mozgawa, W.: The influence of dealumination/desilication on structural properties of metakaolin-based geopolymers. Ceram. Int. **44**(11), 12853–12861 (2018). https://doi.org/10.1016/j.ceramint.2018.04.095
8. Murat, M.: Hydration reaction and hardening of calcined clays and related minerals. I. Preliminary investigation on metakaolinite. Cem. Concr. Res. **13**(2), 259–266 (1983). https://doi.org/10.1016/0008-8846(83)90109-6
9. ASTM D5334: Standard Test Method for Determination of Thermal Conductivity of Soil and Rock by Thermal Needle Probe Procedure (2022). https://doi.org/10.1520/D5334-22
10. ASTM D5930: Standard Test Method for Thermal Conductivity of Plastics by Means of a Transient Line-Source Technique (2017). https://doi.org/10.1520/D5930-17
11. IEEE 442: Guide for Soil Thermal Resistivity Measurements. IEEE Stand. Assoc. (1981). https://doi.org/10.1109/IEEESTD.1981.81018
12. Rode, C., et al.: Nordtest project on moisture buffer value of materials, p. 7 (2005)
13. Seng, B., Magniont, C., Lorente, S.: Characterization of a precast hemp concrete. Part I: physical and thermal properties. J. Build. Eng. **24**, 100540 (2019). https://doi.org/10.1016/j.jobe.2018.07.016
14. Walker, R., Pavía, S.: Moisture transfer and thermal properties of hemp–lime concretes. Constr. Build. Mater. **64**, 270–276 (2014). https://doi.org/10.1016/j.conbuildmat.2014.04.081
15. Zerrouki, R., Benazzouk, A., Courty, M., Hamed, H.B.: Potential use of matakaolin as a partial replacement of preformulated lime binder to improve durability of hemp concrete under cyclic wetting/drying aging. Constr. Build. Mater. **333**, 127389 (2022). https://doi.org/10.1016/j.conbuildmat.2022.127389