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Substitution of Lime by Quarry Co-products in Hemp Concrete: Impacts on Mechanical and Thermal Properties

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Abstract

In the last decades, bio-based building materials have regained interest in a global warming acceleration context. Hemp concretes, composed of hemp aggregates and binders (mostly lime or cement), are nowadays regularly investigated. Their good hygrothermal properties and the use of fast-growing bio-based resources that can store carbon in the building stock during its lifetime are their major features. However, the use of hydraulic binders in their composition presents some drawbacks with their embedded carbon footprint, thus the partial or full replacement of these binders with unfired clayey materials can be relevant. In this study, the use of different clayey quarry co-products, washing sludge, in replacement of traditionally used hydraulic lime is investigated. In laboratory, the studied materials are processed at a same rheological state that is equivalent to the on-field consistency of a conventional sprayed lime-hemp concrete. The hemp/binder ratio is remaining constant as far as possible. Two main issues are targeted in this work. Firstly, with a given clayey material one first aim is to highlight the effect of the reduction of lime content (from 20% to 2% in mass of the clayey binder) on dry mechanical properties (density, compressive strength) and thermal conductivity of these hemp concretes. Then at a given clay/lime ratio (lime addition of 10% in mass of the clayey binder) three other clayey materials are studied to highlight the effect of their variability (clay activity, particle size distribution, mineralogy) on the same properties. The first obtained results display the fact that the lime content reduction for a given clayey binder seems to lead to higher thermal conductivity, higher dry densities, and higher dry compressive strengths. For this given material the thermal conductivities (measured at 10 °C at dry state) are ranging from 0.06 to 0.072 $W.m^{-1}.K^{-1}$,(better than the conventional performances of lime hemp concretes) while their dry densities are ranging from 250 to 350 kg/m^3. The second study highlights the fact that the mechanical and thermal properties of hemp concrete are much more impacted by the variability of clayey part of the binder. For all of the studied materials the thermal conductivities (measured at 10 °C at dry state) are ranging from 0.06 to 0.11 $W.m^{-1}.K^{-1}$, while their dry densities are ranging from 250 to 600 kg/m^3. For some clayey materials that displayed low clay activity the hemp/binder ratio was modified in order to obtain a suitable consistency to be processed. Finally, the use of clayey quarry co-products in replacement of hydraulic lime in the binding phase of hemp concretes seems to be easily achievable, leading to robust thermal and mechanical behavior if the clayey materials is carefully chosen. It also seems possible to adapt the mix compositions to the variability of clayey materials with weaker thermal performances.

Keywords

Hemp concrete, Clayey binder, Hydraulic lime, Hygrothermal properties

Introduction

In the actual context of global warming there is a strong need to assess the greenhouse gases emission problem. The building sector is responsible of a consequent part of this global emissions, and it is partly due to the massive production of cement-based materials [1]. This sector is also consuming large quantities of natural materials that could, locally, become scarce [2]. Regarding these issues, the development of less polluting building materials such as earthen materials has recently regained a strong interest from this industry [3]. Also, the need to better insulate the existing and future buildings is now mandatory to reduce energy consumption of buildings [4]. By developing bio-based insulating materials, using earthen binders the potential to reduce carbon footprint of the building sector is concrete. This study focus on the potential use of clayey resources to replace lime as binder in lime-hemp insulating materials. In this paper the ability of 4 different quarry co-products to be efficient binders is investigated to better understand the influence of their variability on mechanical and thermal properties of the formulated bio-based concretes. To obtain comparable results, all of the formulated materials are processed at a given consistency, equivalent to the on-field consistency of a conventional sprayed lime-hemp concrete, and as far as possible, the hemp/binder ratio is remaining constant. For a reference clayey mud, the effect of the reduction of lime content (from 20% to 2% in mass of the clayey binder) is studied, and for a given lime content of 10% in mass of the clayey binder the influence of the clayey mud properties is studied for 4 different resources.

First a consistency tuning step were conducted, to aim for a same rheological state for the different formulations. Then some mechanical properties of the formulated bio-based concretes were assessed. Finally, their thermal properties were measured and compared.

Materials and Method

Materials

Four different kinds of quarry co-products were studied. All of them were clayey mud, washing fines extracted from different Breton quarries: CM H (Reference washing mud), CM E; CM V and CM G. Figure 1 displays the particle size distribution of these fine earthen materials obtained by laser diffraction. Table 1 highlights some of their geotechnical properties, such as Atterberg limits and methylene blue value. The materials used were of nanomaterials.

The lime that was used in this study, is a commonly used mix of air lime, hydraulic lime and pozzolan sold under the trademark Tradical® PF70.

The hemp that was used in the mix is an industrial hemp sold under the label Chanvribat®. For each formulation the hemp/binder ratio remained constant at 0.55 except for CM V, for which this ratio was 0.3, because of the impossibility to include more hemp fibres due to the low volume of binder.

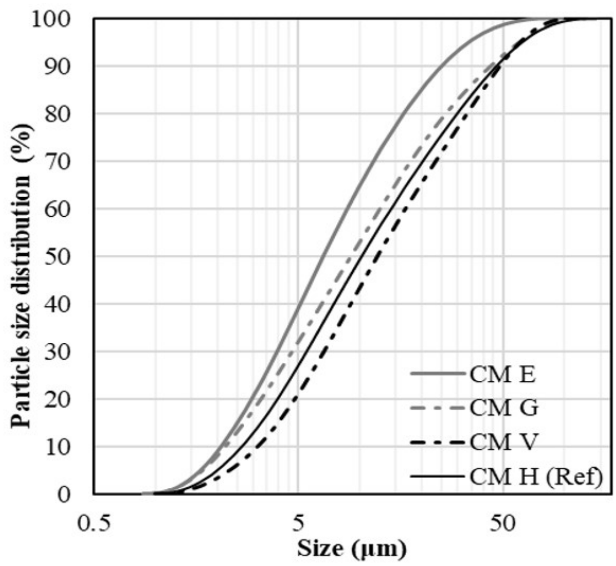

Figure 1: Particle size distributions of the 4 earthen materials.

Table 1: Some geotechnical properties of the studied clayey quarry co-products.

Type of Clayey Mud	CM H (Reference)	CM E	CM V	CM G
Liquid limit W_l (%)	64.6	43.4	75.3	78.1
Plastic limit W_p (%)	27.7	22.5	30.2	29.9
Plasticity index	36.9	20.9	45.1	48.1
Methylene Blue Value	2.1	1	0.95	3.96

Table 2: Description of the different hemp-concrete formulations tested to assess mechanical and thermal properties.

Formulation - CM Type and Lime content (L)	Water/Binder ratios	Number of cubic samples (100 x 100 x 100 mm³)	Number of plate samples (50 x 250 x 250 mm³)	Hemp/Binder ratio
CM H + 20% L	3	3	1	0.55
CM H + 10% L	3.5	3	1	0.55
	3.1	3	1	0.55
	2.8	3	1	0.55
	2.5	3	1	0.55
CM H + 8% L	3.15	3	1	0.55
CM H + 6% L	3.1	3	1	0.55
CM H + 4% L	3.05	3	1	0.55
CM H + 2% L	2.5	3	1	0.55
CM E + 10% L	1.65	3	1	0.55
CM V + 10% L	0.95	3	1	0.3
CM G + 10% L	1.6	3	1	0.55

This could be a first hint that highlights the influence of clay activity on formulation of earth-hemp samples.

All the samples were cast in laboratory at a "sprayed lime-hemp concrete" consistency. Two sizes of samples were studied: 100 x 100 x 100 mm^3 cubic samples for mechanical properties and 250 x 250 x 50 mm^3 plate samples for thermal conductivity measurements.

In this study report, following the rheological tuning section, table 2 resumes all of the samples that were studied for each formulation.

Methods

Rheological assessment

For each of the tested mix, a given rheological state based on the consistency of conventional sprayed hemp-lime material was aimed. It had to correspond to a water-lime ratio of approximately 1.4. To reach this aimed consistency two methods were intended, to assess this consistency and to aim for it for each formulation.

First, yield stress of the reference lime-water mix was measured at low rate ($\dot{\gamma} = 0.01\ s^{-1}$) using an Anton Paar MCR 702 rheometer equipped with vane geometry, immediately after mixing, as in Perrot et al. study [5]. The vane geometry tool that was used present a 13 mm R_1 radius, a 40 mm H height and a 11 mm R_0 radius. A yield stress τ_0 was thus determined using equation (1) for this reference mix (narrow gap hypothesis, homogeneous shear stress). Then for each formulation, aiming for this yield stress τ_0 eased the adaptation of each earth-lime mix consistency.

$$\tau_0 = \frac{M}{2\pi R_0^2\left(H + \frac{R_0}{3}\right)} \quad \text{with M: Measured torque peak value (N.m)} \qquad (1)$$

Also, this reference yield stress was assessed using a slump/spreading flow test widely used in literature, using the equation (2) suggested by Roussel and Coussot [6], taking into account. This method also allowed for each formulation, to aim for a yield stress τ'_0, and thus to the targeted consistency.

$$\tau'_0 = \frac{225\rho g\Omega^2}{128\pi^2 R^5} \qquad (2)$$

Mechanical tests

Compressive tests were carried out with a 3R®Synthax press with a 50 kN stress sensor. The strain was measured with the plate displacement. All the samples that were tested were approximatively 100 x 100 x 100 mm^3 cubic samples and were dried in oven at 45 °C until mass stabilization before testing. Two directions were studied for each formulation to highlight the anisotropic behavior of these samples, a direction parallel to the manufactured layers and a direction perpendicular to these layers, in each figure these directions (parallel or perpendicular) will be notified for each dataset. The tests consisted in a simple loading range at a constant rate of 1 mm/min during 10 min and the compressive stress at 1% and 2% strain were measured for each sample. For each sample the dry density was determined before compressive test. No elastic modulus was measured in this campaign, the press being slightly inaccurate for elastic modulus measurements.

Thermal conductivity measurements

For each formulation, a 250 x 250 x 50 mm^3 sample was processed and placed inside a heat flow meter apparatus to measure its thermal conductivity following the ISO 8301:1991 international standard [7]. The experiments were here performed at mean temperature of 10 °C and 23 °C, the hot and cold plate set to ensure a 10 °C temperature difference as in El Assaad et al. study [8]. The measurements were conducted on dried samples (in oven at 45 °C until mass stabilization) to ensure a relative humidity of approximately 0% during the test, as the moisture can affect the measurements [8]. Measurements obtained at 10 °C are mostly used in certification experiments before marketing while 23 °C measurements are more spread in the scientific community to have comparable results.

Results and Discussion

Consistency tuning

The first part of this study consisted of a consistency tuning step for the binding phase of these bio-based concretes, in order to reach a comparable consistency for each studied formulation. The reference consistency was defined by water and PF70 lime, at a water-binder ratio of 1.4. The obtained apparent yield stress to aim for were the following: τ_0 = 3.46 Pa and τ'_0 = 0.77 Pa. For each formulation of binding phase, the optimum water/binder ratio to aim for was thus determined. Table 3 displays these optimum ratios for each studied formulation.

In this study, another aim was to understand the influence of a variation in this water-binder ratio on the thermal and mechanical properties. Thus, for the reference formulation CM H + 10% Lime, samples at various water-binder ratios were made: W/B = 2.5, W/B = 2.8, W/B = 3.1, and W/B = 3.5. All of the tested sample's formulations are listed in table 2.

Mechanical properties

For each formulation, mechanical tests were carried out. Figure 2 displays the results obtained for the reference clayey mud CM H, for different testing direction or different water/binder ratio at a given hemp/binder ratio of 0.55. The unconfined compressive stress (UCS) measured at 1% or 2% strain is plotted versus the apparent dry densities of the samples or ver-

Table 3: Optimum Water/Binder ratios for a "sprayed lime hemp" consistency.

Mix Design	Optimum Water/Binder ratio			
	CM H (Reference)	CM E	CM V	CM G
CM + 20% Lime	3	-	-	-
CM + 10% Lime	3.1	1.65	0.95	1.6
CM + 8% Lime	3.15	-	-	-
CM + 6% Lime	3.1	-	-	-
CM + 4% Lime	3.05	-	-	-
CM + 2% Lime	2.5	-	-	-

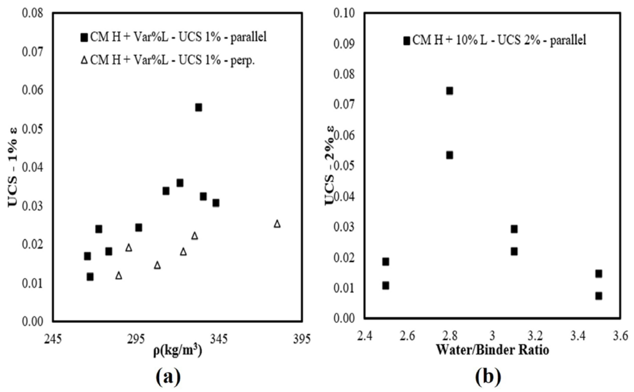

Figure 2: Influence of direction, dry density, and water-binder ratio on mechanical properties of earth-lime-hemp materials.

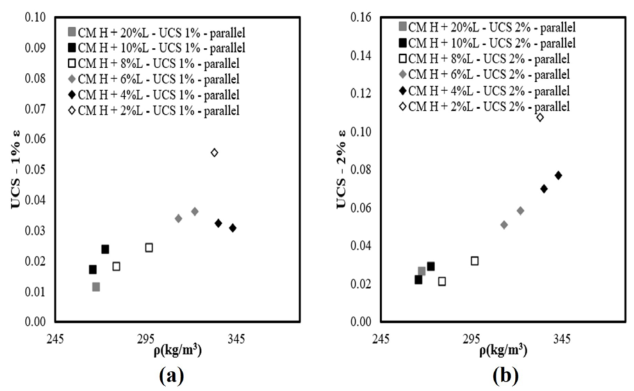

Figure 3: Influence of lime content on the mechanical properties of a given bio-based concrete.

sus the water/binder ratio. It appears in figure 2a that in these conditions, the parallel tests ensured systematically higher mechanical properties, which is a good point for a sprayed bio-based concrete, since it is representative of in-service loading conditions. For the rest of the study, this direction will be analyzed. However, the measured UCS at a 1% strain seems to be slightly low according to the literature values currently ranging from 0.2 to 0.4 MPa [9]. These low apparent UCS could be due to the method of measurement of this UCS: here the choice has been made to reduce the tolerated strain to 1% or 2% were in the literature, the measured UCS is frequently the maximum stress before irreversible deformations (at higher strains than 1% or 2%) [10]. Another fact that could explain these low mechanical properties is the high water/binder ratio and the relatively low hemp/binder ratio. Other experiments should be conducted on formulations of materials with hemp/binder ratios ranging from 0.55 to 1 or more to optimize the granular matrix of these bio-based concretes. In figure 2b it also appears that the change in water/binder ratio for a given mix (CM H + 10% Lime) and a relatively low hemp/binder ratio (0.55) leads to different UCS, mainly conducted by the change in dry density. It is fair to assume that for a given mix design (hemp/binder ratio and earth/lime mix), it exists an optimal water/binder ratio to reach an optimal mechanical strength. Finally, it logically appears that when the dry density of a given material increases, its mechanical strength also increases.

Figure 3a and 3b display the obtained UCS (at 1% strain or 2% strain) versus dry density for different mix of reference CM H and various lime contents. It appears that a reduction of the lime content leads to an increase of the dry density, and thus to an increase of mechanical properties. It seems to be linked to the nature of the binding phase, earthen materials being slightly denser than lime. It is also linked to the changes in water/binder ratio to obtain a given consistency. Further experiments should be led to better understand the influence of a change in binding phase, focusing on clayey activity of the earthen binder, specific densities of lime and earth, hemp/binder ratio, and water/binder ratio.

Finally, figure 4 highlights the influence of clayey binder type on mechanical properties of bio-based concretes. It first appears that the coarsest clayey mud CM V, presenting the lowest methylene blue value (clay activity), processed at the lowest water/binder ratio, with a lower hemp/binder ratio, is leading to the highest densities and strengths. These higher mechanical properties could also lead to higher thermal conductivities. For the 3 other clayey mud, the lowest densities and mechanical strengths are obtained for CM H that was processed at a high water/binder ratio and that present a quite high methylene blue value. For CM E and CM G the water/binder ratio was closed, so the obtained densities are similar, however, for CM G that is finer and presents a high methylene blue value, the obtained mechanical strength seem to be higher.

From these observations, some conclusions could be reached. Since the density seems to drive the mechanical properties of bio-based concretes, it could seem appropriate to aim for low hemp contents, but that could be counterproductive in terms of thermal properties. An equilibrium should be found between mechanical properties and hemp content: further experiment should be conducted, but it is likely that it exists an optimal hemp/binder ratio that could allow sufficient mechanical strength, with low thermal conductivity. Also, the methylene blue value and particle size distribution of a given earthen could be hints to estimate a mechanical strength at a given density for a given hemp/binder ratio with further

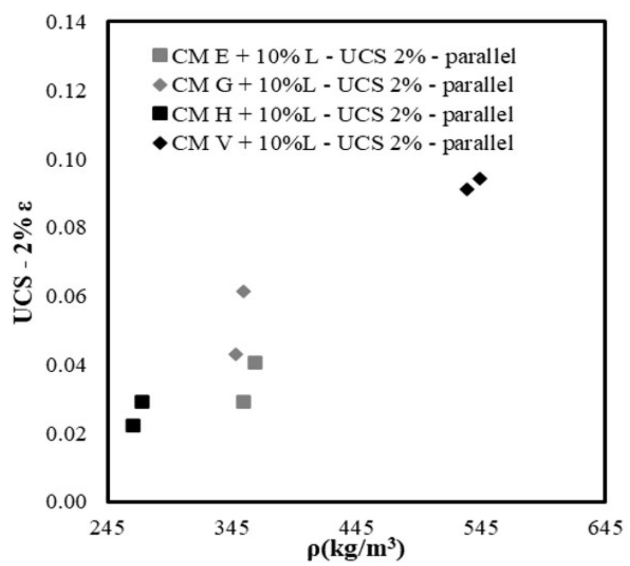

Figure 4: Influence of type of clayey mud on mechanical properties of bio-based concretes.

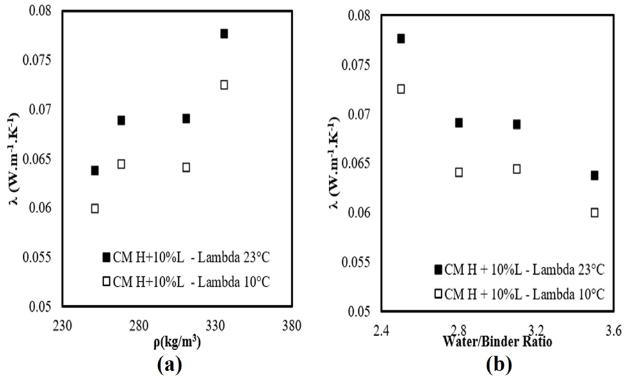

Figure 5: Evolution of thermal conductivities of CM H + 10% L for different densities and water-binder ratios.

experiments as it is already used in earthen building materials formulation [9, 11]. Also, in this study, some measurements are missing such as elastic modulus, and it could also be a subject for future experimental campaigns.

Thermal properties

Finally, for each tested formulations, thermal conductivity was measured on dedicated samples at the dry state with an HFM apparatus at mean temperatures of 10 °C and 23 °C. Figure 5 displays the obtained results at 10 °C and 23 °C for CM H + 10% Lime (reference) at different water/binder ratios at a given hemp/binder ratio of 0.55. It appears in figure 5a that thermal conductivity logically increases when the dry density of the specimens increases. However the range of obtained thermal conductivities is quite good for hemp concrete, ranging from 0.064 W.m^{-1}.K^{-1} to 0.078 W.m^{-1}.K^{-1} at 23 °C and from 0.06 W.m^{-1}.K^{-1} to 0.072 W.m^{-1}.K^{-1} at 10 °C. In figure 5b it appears that, at a given hemp/binder ratio, a reduction of the water/binder ratio would lead to higher thermal conductivities (because of higher densities).

Figure 6a displays the variation of thermal conductivity for CM H with various lime contents. As the lime content is increasing, the water/binder ratio is mostly increasing, and the obtained dry density is decreasing. Thus, the thermal conductivity is lower for a higher lime content (20%). Figure 6b highlights the influence of clayey mud type on obtained densities and thermal conductivities. As it was expected, CM V, with high densities due to low water/binder and hemp/binder ratios is leading to high thermal conductivities around 0.1 W.m^{-1}.K^{-1} when CM H is leading to the lowest thermal conductivities, due to high water/binder ratio and low densities. At comparable densities (near 330 kg/m^3), the less active clayey mud CM E is leading to lower thermal conductivities (lowest mechanical strength, λ = 0.06 W.m^{-1}.K^{-1}) than CM G (most active earthen material, higher mechanical strength, λ = 0.1 W.m^{-1}.K^{-1}). For this range of densities, CM H, that presents an intermediate clay activity, allows to reach intermediate thermal conductivities between 0.07 and 0.08 W.m^{-1}.K^{-1}.

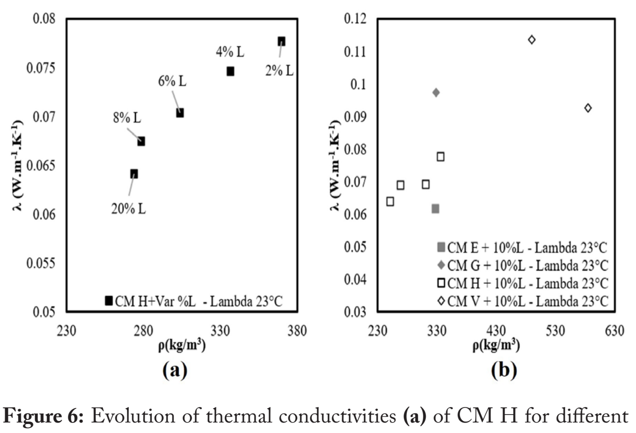

Figure 6: Evolution of thermal conductivities **(a)** of CM H for different lime contents and **(b)** for various clayey muds as binder.

Conclusion

In this study several tests were conducted. First the aim was to develop a sprayed hemp concrete with a reduced use of lime in its composition replaced by different clayey muds as binders. The potential use of these earthen resources seems to be promising, since the obtained results led to thermal conductivities ranging from 0.06 W.m^{-1}.K^{-1} to 0.1 W.m^{-1}.K^{-1}. However, some further experiments should be conducted in order to better formulate these hemp-concretes. First there is a need to study various processing methods (such as compacted earth-hemp blocks) and various hemp/binder ratios. This could allow to reach better mechanical strength at low densities for maintained thermal performances. Also, with these experiments conducted on a given earthen binder could help to build a predictive model as in Tronet et al. study [10], that could link hemp/binder ratio, compaction energy and water/binder ratio to better control the final properties of the formulated hemp concrete. Also, further investigations should be conducted to obtain more consistent mechanical properties such as mechanical strength (maximum stress before irreversible deformations) and elastic modulus at low strain. Finally further experiments should be conducted following the previous recommendations for different earthen binders (clayey muds) to better understand the influence of clay variability on final properties of formulated bio-based concrete. These potential experimental campaigns should help to design robust formulations of earth-hemp concretes that could be industrially produced by being compacted or sprayed, with as little amount of lime as possible.

Acknowledgments

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Conflict of Interest

None.

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