Hemp-Clay Concretes for Environmental Building—Features that Attribute to Drying, Stabilization with Lime, Water Uptake and Mechanical Strength

Monika Brümmer, Mª Paz Sáez-Pérez and Jorge Durán Suárez

Abstract There are numerous parameters which define the mechanical properties of hemp concretes. Several authors identified significant differences in mechanical properties due to the quality, particle size, form and distribution of the hemp aggregates, and also due to the energy of compaction, binder dosage, density, drying conditions and drying time. The other factors which influence the mechanical properties of hemp concretes are the type of binders and their influence on the setting process of mortars containing plant aggregates. This research work has been done to encourage the use of hemp in construction industries that can reduce the usage of industrial binders and shift the focus on natural binders. The experiments were carried out to observe the drying kinetics, capillary water uptake and mechanical strength of hemp-clay concretes made with de-fibered or non-de-fibered hemp materials of industrial and domestic origin. The influence of addition of the lime on the mechanical performance of hemp-clay composites was also studied.

Keywords Hemp · Concrete · Hurds · Fiber · Waste · Lime

M. Brümmer
Ph.D. Program in History and Arts (Territory, Heritage and Environment), University of Granada, Cannabric, Cañada Ojeda 8, 18500 Guadix, Spain
e-mail: mbrummer@correo.ugr.es; cannabric@cannabric.com

M.P. Sáez-Pérez (✉)
Department of Architectonic Constructions, Advanced Technical School of Building Engineering, University of Granada, Avenue Severo Ochoa, Fuentenueva Campus, 18071 Granada, Spain
e-mail: mpsaez@ugr.es

J.D. Suárez
Department of Sculpture, Faculty of Fine Arts, University of Granada, Granada, Spain
e-mail: giorgio@ugr.es

R. Fangueiro and S. Rana (eds.), *Advances in Natural Fibre Composites*,
https://doi.org/10.1007/978-3-319-64641-1_21

Introduction

Bio-based materials from rapidly renewable resources provide the opportunity to create a new generation of low energy and carbon storing building products [6] with improved insulating properties. In this manner they are reducing greenhouse gas emissions caused by human activities [20] and replacing natural resources made from mineral aggregates [27]. It is widely assumed that renewable materials are environmentally beneficial and should be preferentially used in building envelopes to reduce the energy needed for manufacturing processes and air conditioning in the building sector, which is responsible for about 50% of the energy consumption worldwide [7]. The economic production and processing of natural fibers [9] is an added motive for the increasing research in this field in the last decade [27]. Hemp (*Cannabis sativa* L.) stands for a fast growing [17, 24] and multi-beneficial [2, 11, 29, 33] fiber plant. Its world-wide spread as one of the earliest culture plants [2, 29] is also explained by its easy acclimation to different climates, altitudes and soil types and its important role in crop rotations [2, 33, 34]. The use of plant aggregates in concretes and mortars is a method that allows versatile applications in construction, and practiced since antiquity to improve or modify their qualities [4, 5]. To ensure their major appraisal and use, building-product and green building designers must understand hemp based building materials in terms of their thermal, acoustic, hygrothermal and mechanical performances, in particular the links between these features. Hemp concretes, based on hemp hurds and lime binders, are proving since the early years 90s to be a user friendly, high performance and fire-resistant construction material for light weight applications in new building and renovation works [8]. However, hemp concretes have an elastic-plastic behavior and are therefore, reported to function with a support structure [10]. A lower mechanical strength of plant based concretes as compared to the mineral ones is considered as the major drawback for their use in construction [27]. An interesting challenge is, therefore, the refinement of the mechanical performance of plant based concretes for structural purposes. By now, it is demonstrated that the compressive strength of hemp concretes, with unchanged hemp content, can be increased by compaction [28], through further reduction of void volume by adding small sized aggregate or by shortening the mean particle length [1, 32]. As reported by several authors, adding fibers could not improve significantly the mechanical strength of hemp concrete formulations with lime, cement or gypsum [15, 26] but could be an interesting option for regions without facilities to separate stem materials [14]. However, very few studies are carried out on this matter, and therefore, the present research investigates the mechanical properties of hemp concrete, comparing the performance of de-fibered and non de-fibered stem material in a lime stabilized hemp-clay concrete matrix. Improving mechanical strength of hemp concretes by augmenting the dosage of lime or other calcined binders is possible [26] but it is not favorable, as the highest negative contribution to their climate change indicator is caused by commercial binders [28]. These materials consume 49% primary energy and 68% water of the total consumption of a hemp concrete and cause 47% of corresponding air pollution, followed by the wooden structure, plasters and hemp hurds [20]. Furthermore, in plant based concretes, setting problems occur [16] through the release of polysaccharides [18, 28], that hinder the carbonation of aerial lime; while in mortars with mineral aggregates, up to 90% of the CO_2 emitted during its calcination is re-absorbed [21]. A design that takes into account the local raw clay binders with the lowest possible environmental impact [30] and involving minimum transport is decisive for the final carbon footprint of a hemp concrete. It also takes into account the dosage, constructive systems (e.g. in harmony with traditional and climate adapted building) and application technology [19]. The motive of this research work is the development of hemp concretes for alternative economic development, based on the local hemp waste material of an ancestral hemp variety found in the Moroccan Central Rif, and historically harvested for industrial as well as recreational purposes. The use of both *C. sativa* L. and *C. sativa* L. - *indica* species as fiber hemp is undertaken by numerous archeological [11, 22] and written [2] affirmations. Due to technological obstacles, plant's specific morphological reasons and chemical differences between hemp hurds and fibers [25], whole stem utilization has been taken into account and compared with de-fibered stem material. The present study also aims to reveal if the plant infusions of both species have influence on the drying process of clay based mortars and on the interactions between clay and lime.

Materials and Methods

Hemp Materials

There exist significant variations in wood anatomy, wood cell distribution, cell wall thickness and cell dimension between *Cannabis sativa* L. and *Cannabis sativa* L. - *indica* species [2, 3]. Also, the chemical composition of bark differs from the woody stem material and hemi-cellulose is more abundant in the hemp core (31%) than in the bark (13%) [34]. In addition, the absorption capacity is more in the core than in the bark [23] and water and alkali soluble components increase with the maturity of the plant [13]. The present research focuses on both, industrial *Cannabis sativa* L. hemp, collected in Cervera del Rio Alhama (Spain) and ancestral *Cannabis sativa* L. - *indica* hemp (Fig. 1), collected in Morocco's "historic hemp farming region" [12]. Absorption of 5 g sample from each species of hemp core and hemp fiber was observed in the intervals of 72 h, 7 days and 14 days, and for studying the drying kinetics, the total water loss after drying in T20 and HR80 conditions was recorded. The plant materials were prepared by manual chopping. In addition, plant infusions were produced by submersion for 14 days, for the elaboration of lime stabilized earth mortars. Furthermore, hemp-clay concretes were produced to understand the differences in the use of industrial hemp hurds from Cavac (France), with a mean particle length of

Fig. 1 Moroccan hemp stalks of "beldiya"

2–25 mm (Fig. 2) and whole stem material from Cervera del Rio Alhama (Spain), cut parallel to the stem section in pieces of similar length (Fig. 3), with a chopping machine used for agricultural waste.

Binder and Stabilizer

For the preparation of mortar samples, earth was collected from the same region where the ancestral *C. sativa* L. - *indica* hemp materials were collected. For the analysis of its clay minerals, the fractions smaller than 2 μm have been separated after decanting the suspension of 200 g earth in 500 ml of water for 8 h. Liquids, obtained from the upper 10 cm of the column of liquid with particles, were collected and centrifuged for 4 min at 6000 revolutions. Mineralogical X-ray diffraction (XRD) analysis was done with a PANalytical X'Pert Pro diffractometer, equipped with a X'Celerator solid state detector, and using Cu-Kα radiation at 45 kV and 40 mA. The diffraction patterns were obtained by continuous sweeping between 3 and 50° of 2θ, with a space of 0.01° of 2θ and 20 s of time in each step. Its clay minerals (fractions of 2 μm) contain 18.1% quartz, 44.1% illite, 22% chlorite and 15.8% amorphous particles. Illite is a clay mineral formed by alteration of feldspars. It is expensive and of medium plasticity and have unctuous touch and low permeability. Illite from Issaguen is sodic and it dissolves rapidly in water. Its red color is associated with iron oxides. Its structure is mica type, but it has less

Fig. 2 Industrial hemp hurds (France)

Fig. 3 Chopped hemp stem (Spain)

potassium than muscovite, more inter-laminar water, and less substitution of aluminum for silica in the tetrahedral layer. Chlorite is found in nature combined with illites. It is not very expensive, has less cut resistance, and is difficult to disperse in water. This clay has tetrahedral-octahedral-tetrahedral (TOT) packages. For the stabilization of the clay as reinforcement of the inter-laminar matrix to resist the weathering conditions, white natural hydraulic lime NHL3.5 "Calcia" from Socli (France) was used and showed superior results in a previous research with different hemp-lime mortars [4].

Experimental Program with Clay Mortars and Plant Infusions

Infusions from the 14-day submersion of two hemp varieties (Figs. 4 and 5) have been used to prepare earth mortars with the addition of NHL3.5 lime.

In addition, a control mold was also made, and kneaded with water. The hemp infusions were obtained from a quantity of plant material corresponding to this mold size, employing 1 m^3 of plant material per m^3. The infusions have been prepared using a water-plant material ratio in such a way that the suitable amount is obtained to knead the mortars, taking into account that part of the water is absorbed by hemp. Plant materials were previously cut into pieces to obtain a similar length that is found in commercial hemp hurds (maximum 25 mm) after separating fibers and hurds. After immersion in closed containers, hemp infusions got darkened and gave off a smell in hemp hurds distinct from the whole stem material. Before mixing, the red earth of Issaguen has been sieved at 3 mm maximum grain size. Four different specimens have been made, one of each class, in standardized molds of 4 × 4 × 16 (cm). The first specimen ("A") contained sieved earth, NHL3.5 lime and potable water. The second one ("FPK") was prepared with sieved earth, NHL3.5 lime and hemp infusion of the full stem section of the ancestral Moroccan hemp variety, called locally "beldiya" [12]. The third specimen ("PK") was made with sieved earth, NHL3.5 lime and hemp infusion from the de-fibered stem material of Issaguen. The fourth specimen ("FPE") was prepared like the second one but with the infusions obtained from industrial hemp of Cervera del Rio Alhama (Spain) (Fig. 6).

The kneading was performed with equal proportions of water or hemp infusion by weight. The percentage of NHL3.5 lime was high, 25% by volume in relation to

Fig. 4 Moroccan hemp core and fiber after 14 days of submersion in water and drying

Fig. 5 Spanish hemp core and fiber after 14 days of submersion in water and drying

Fig. 6 Earth mortar specimens kneaded with water or plant infusions

the earth in order to improve the results and to study if the substances released by the plant material also affect the drying kinetics, and to compare the results with the specimen mixed with water. After 28 days of curing at temperature of 20 °C and RH of 80%, the mortar samples were analyzed using mineralogical X-ray diffraction (XRD) in order to verify if the minerals of clay and lime were associated.

Experimental Program with Lime Stabilized Hemp-Clay Concretes

For both hemp-clay concrete (Fig. 7) formulations, with either hemp hurds or chopped hemp stem (including the fibers) plus sieved earth and water, two different percentages of NHL3.5 lime (8 and 16% in volume) were added. This stabilization aimed to reinforce the inter-laminar matrix of the clay through cationic exchange and transformation of peripheral links to provide good resistance to local weather conditions (Central Rif has the highest precipitation rate in Morocco). The use of lime is encouraged due to the fact that it was found in the formulation of all traditional earth concretes and mortars used in the region, although it is not produced locally. During a curing and drying period of 5 weeks at T20 and RH80 conditions, drying kinetics was studied. After 5 weeks, when all concrete samples were in equilibrium with the relative humidity of the ambient, capillary water uptake was measured, according to the Spanish norm UNE-EN1015-18:2003. Mechanical results were obtained at an age of 37 days instead of 28 days because drying progressed slower than in mineral concretes. Compressive and flexural strength of the concretes were tested at Applus laboratory (Barcelona), according to the Spanish norm UNE-EN1025-11:2000/A1:2007, with four standardized rectangular concrete samples ($4 \times 4 \times 16$ cm) of each type, obtaining four specimens for the test of the flexural strength and eight specimens for the test of the compressive strength.

Fig. 7 Lime stabilized hemp-clay concrete test specimens

Results and Discussion

Influence of Plant Infusions on Drying of Lime Stabilized Earth Mortars and the Interaction Clay-Lime

Among the four different lime stabilized earth-mortars, a higher viscosity has been observed in the ones prepared with infusions that contain whole stem material. Under conditions of T20 and RH80, the specimen mixed with water advanced faster during the drying process of the first week, but the total water loss after 4 weeks was lower than in the specimens with hemp infusions. In the specimen made with infusion of whole stem material, deviations from the mortar sample “A” were higher than in the specimen with infusion of hemp core material. Even so, the final water loss % (by weight), as compared to the initial weight of the fresh mortars, varied a little in the different specimens, being 23.74% in the mortar mixed with water, 24.06% in the mortar mixed with infusion of core of the ancestral hemp variety, 25.89% in the mortar with infusion of whole stem material of the same and 26.63% in the specimen made with whole stem material of industrial hemp. According to these numbers the mortars with higher initial viscosity showed higher final water loss. The XRD tests that were performed with 28 days cured specimens and with fractions of less than 200 μm (Fig. 8) showed that in mortars kneaded with hemp infusions, a delay occurred in the carbonation of the lime that is not combined with the clay minerals, as well as in the combination of the rest of the lime with the clay as compared to the mortar sample mixed with water.

In the mortar sample “A”, which has been kneaded with water, all clay minerals have reacted with NHL3.5 lime (they no longer appeared as such). The lowest percentage of carbonated lime was observed in the sample “PK”, made with hemp

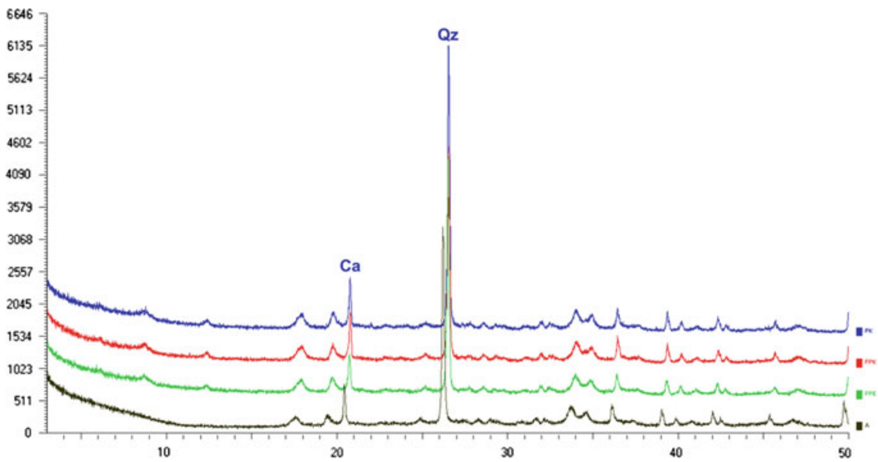


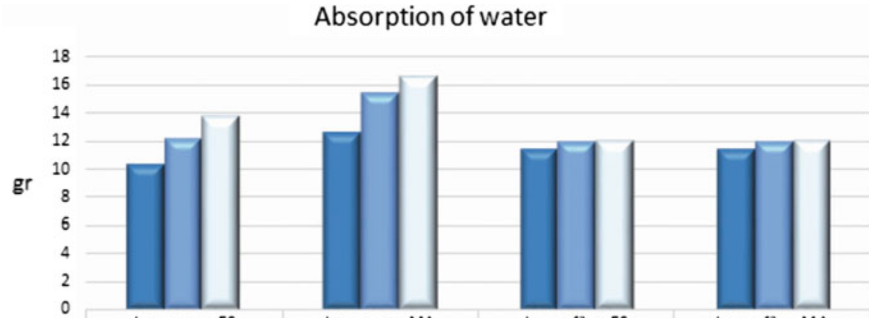
Fig. 8 Mineralogical X-ray diffraction of earth mortar specimens mixed with water (*black*) or infusions of plant materials (*green*, *red* and *blue lines*)

core infusion, i.e. 1.5 against 7.1% of calcite in the mortar mixed with water; while the samples with whole stem material showed 2 and 2.2% (Table 1).

This can be explained by the higher percentage of hemi-cellulose present in hemp core compared to the bark fraction [34] and the higher water absorption by the hemp stem material, compared to the bark [23], resulting in higher release of substances that hinder the hardening processes. The calcite content was slightly higher in “FPE” than in “FPK” specimen. This can be explained by variations in the wood anatomy, wood cell distribution, cell wall thickness and cell dimension between *C. sativa* L. - *indica* and *C. sativa* L. species [2, 3]. The submersion and drying tests of the plant materials confirmed a higher porosity of the ancestral *C. sativa* L. - *indica* hemp. A clearly higher and quicker water absorption has been observed in the ancestral hemp core, compared to *C. sativa* L. hemp core during the period of submersion, whereas no differences were observed in the fibers of both raw materials (Fig. 9). In all specimens the total water loss after drying was higher than the amount of water absorbed by submersion. While 5 g of *C. sativa* L. - *indica* hemp core absorbed 16.63 g of water in 14 days and lost 17.13 g in 6 days, *C. sativa* L. hemp core only absorbed 13.75 g and lost 14.25 g. These facts were probably attributed to the bigger pore size of the earlier matured *C. sativa* L. - *indica* hemp and an irreversible swelling of hemp core material during water absorption, as observed at micro-scale [5]. The quantitative analysis of lime-stabilized clay mortars (Table 1) verifies that specimens with infusions of Issaguen’s hemp stem show the highest percentage of uncombined clay among all samples. In “FPE” specimen with industrial hemp stem it is mainly illite that got associated with lime, whereas in the specimen “FPK”, with infusions of Issaguen’s hemp stem, it is rather the chlorite. “FPE” specimen showed 27.7% free illite and 15.2% free chlorite and “FPK” specimen showed 42.2% free illite and 11.5% free chlorite, whereas in the sample mixed with water all the clay mineral matrixes got combined with lime.

Table 1 Quantitative analysis by mineralogical X-ray diffraction of earth mortar specimens

Quantitative analysis (%)	A	PK	FPK	FPE
	With water	With infusion of hemp core (Issaguen)	With infusion of whole stem material (Morocco)	With infusion of whole stem material (Spain)
quartz and silicates	73.2	36.3	30.1	42.2
illite	–	42.2	42.2	27.7
chlorite	–	10.4	11.5	15.2
calcite	7.1	1.5	2	2.2
amorphous	19.7	10.7	14.2	12.7



	hemp core ES	hemp core MA	hemp fiber ES	hemp fiber MA
72 h	10,38	12,63	11,50	11,50
7 days	12,25	15,50	12,00	12,00
14 days	13,75	16,63	12,00	12,00

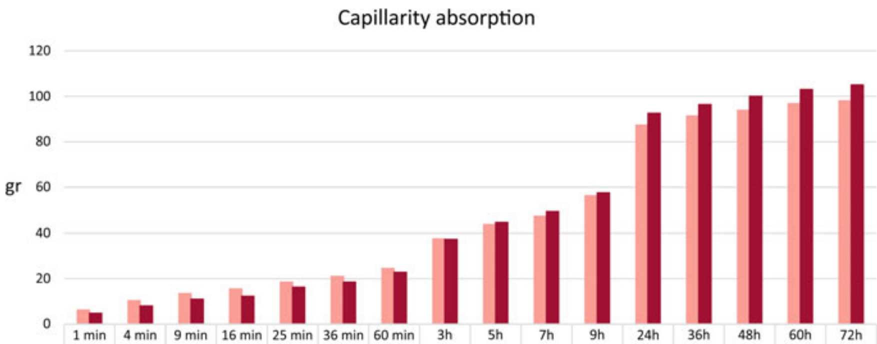
Fig. 9 Absorption of water in grams by submersion in water of 5 g hemp material (origin: Spain and Morocco)

Drying Kinetics of the Different Hemp Concretes

In the first 72 h, the drying progressed faster in the molds of series 2, stabilized with 16% lime. Then the series 1, stabilized with 8% lime, advanced, until a slightly higher water loss was noticed in the series 2 after 5 weeks of drying. In the molds of series 1, those made with hemp hurds, dried faster in the beginning, while after 24 h the drying of specimens with chopped stem material was advanced. The total water loss of the last one was greater after 5 weeks. In the molds of series 2, those made with hemp hurds dried faster at first, while after 24 h the drying of specimens with chopped stem material was advanced. After the 3 weeks until 4 weeks of age, the specimens made with hemp hurds showed faster drying once more. Nevertheless, total water loss after 5 weeks was greater in the molds with chopped stem material of both series than in those with hemp hurds (in specimens with chopped stem material 347 g and 355.5 g in series 1 and 341.5 g or 334.5 g in series 2, in those with hemp hurds 317 g and 327 g in series 1 and 319 g and 305.5 g in series 2). Therefore, the final water loss was slightly higher in molds, stabilized with a lower amount of lime. According to these results it can be understood that in lime stabilized hemp clay concretes the hemp stem material releases more inner pore water through swelling than the hemp hurds material, possibly due to the higher contact area of the fibers.

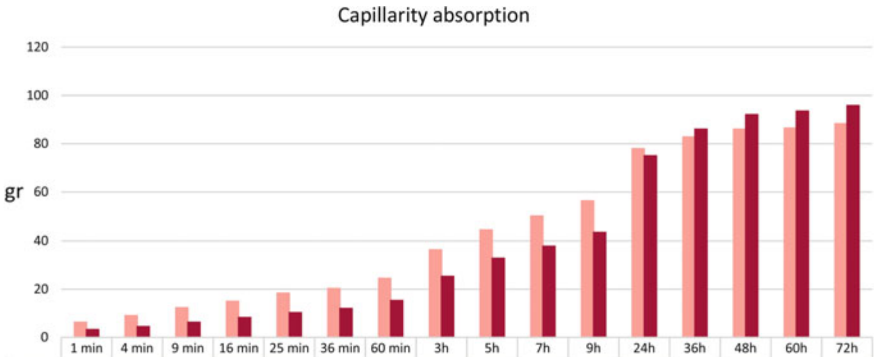
Capillarity Water Uptake of Lime Stabilized Hemp-Clay Concretes with de-Fibered and Whole Stem Material

In the short-term absorption of concretes of series 1, stabilized with 8% lime, molds made with whole stem material absorbed water quicker, whereas after 3 h molds made with hemp hurds became more absorbent. It is expected that the absorption does not end until the full saturation of the hemp hurds is achieved, a process that, as observed in the submersion test, takes more than 14 days in the hemp hurds, whereas 7 days in fiber material (Fig. 10). The molds subjected to capillary absorption of 72 h (Figs. 10 and 11), take more than 3 weeks to dry under T20 RH80 conditions. The whole stem species dried earlier, as did the hemp fibers with respect to the hemp hurds. Comparing series 1 and 2, it can be observed that higher stabilization has a more favorable effect on the specimens with hemp hurds, because the absorption progresses slower from the beginning. However, a higher lime addition benefits practically nothing to the specimens with chopped stem. Till 24 h the absorption of series 2 progressed practically in the same rate as in the samples stabilized with half amount of lime, although after 24 h the absorption advanced somewhat slower than in the series 1. In series 2 the molds with hemp hurds showed more absorption than the molds with whole stem from 36 h and not after 3 h as in the series 1. Finally, the drying of the molds stabilized with twice the lime was slower than in series 1, although previously absorbed water was lower.



	1 min	4 min	9 min	16 min	25 min	36 min	60 min	3h	5h	7h	9h	24h	36h	48h	60h	72h
S1 p+f	6,25	10,30	13,50	15,50	18,50	21,00	24,50	37,50	43,80	47,50	56,30	87,30	91,30	93,80	96,80	98,00
S1 p	4,75	8,00	11,00	12,30	16,30	18,50	22,80	37,30	44,80	49,50	57,50	92,50	96,30	100,00	103,00	105,00

Fig. 10 Capillarity absorption in grams, in specimens of SERIES 1, stabilized with 8% lime, with hemp hurds (S1 p) or chopped stem (S1 p + f)



	1 min	4 min	9 min	16 min	25 min	36 min	60 min	3h	5h	7h	9h	24h	36h	48h	60h	72h
S2 p+f	6,25	9,00	12,30	15,00	18,30	20,30	24,50	36,30	44,50	50,30	56,30	78,00	82,80	86,00	86,50	88,30
S2 p	3,25	4,50	6,25	8,25	10,30	12,00	15,30	25,30	32,80	37,80	43,50	75,00	86,00	92,00	93,50	95,80

Fig. 11 Capillarity absorption in grams, in specimens of SERIES 2 stabilized with 16% lime, with hemp hurds (S2 p) or chopped stem (S2 p + f)

Mechanical Results of Lime Stabilized Hemp-Clay Concretes with de-Fibered and Whole Stem Material

Contrary to the results of another research carried out with lime, cement and gypsum concretes containing hemp hurds and fibers [14, 15], in the present work adding fibers successfully increased the compressive strength as well as the flexural strength of all tested lime stabilized hemp-clay concretes (Table 2 and 3).

Nevertheless, the samples of series 2, stabilized with 16% lime showed worse results in their compressive strength than samples of series 1 stabilized with 8% lime, which showed 1.3 MPa for the specimens with whole stem and 1.2 MPa for the specimens with hemp hurds. The specimens of series 2, stabilized with 16% lime showed 1.26 and 1.18 MPa, respectively. On the contrary, flexural strength was higher in series 2 stabilized with 16% lime than specimens of series 1, which exhibited 0.55 MPa for the specimens with whole stem and 0.43 MPa for the specimens with hemp hurds. The specimens of series 2 showed 0.58 and 0.45 MPa respectively. Although large amounts of plant material, equivalent to one m^3 per m^3 of concrete were used for the specimens of this research, their compressive strengths were within the upper range of adobe bricks that usually range from 0.32 to 2.46 MPa [31] and are frequently found in load-bearing applications. The mechanical performance of hemp concretes is limited due to meso-pores (from 0.1 to 1 mm) formed by trapped air within the hemp aggregates and the binder itself and micro-pores (lower than 0.01 lm) in the binder matrix. 40% in volume of lime binder would be needed to reach a compressive strength of 1.15 MPa by reduction of the macro-pores, that occupy spaces of up to 1 cm between particles of a hemp light concrete [10]. Earth is a cheaper and environmental friendly material to fill those macro-pores. Clay particles from 0.08 up to 2.5 µm, contrary to air and hydraulic lime binders [4], cover all the pores of the wall of hemp hurds but form a heterogeneous structure after drying and thus reduce the contact area with the same [7].

Table 2 Mechanical results series 1 (P + F = whole stem, P = hemp hurds)

Reference	Mass (g) specimens 4 × 4 × 16 (cm)	Flexural strength (37 days)		Compressive strength (37 days)	
		Load (N)	Tensile (MPa)	Load (N)	Tensile (MPa)
S1 P + F (a)	275.28	234	0.5	2.037	1.3
				2.026	1.3
S1 P + F (b)	274.59	230	0.5	2.163	1.4
				2.261	1.4
S1 P + F (c)	270.81	238	0.6	2.062	1.3
				2.137	1.3
S1 P + F (d)	280.02	253	0.6	2.192	1.4
				2.097	1.3
S1 P (a)	271.18	173	0.4	1.887	1.2
				2.070	1.3
S1 P (b)	269.91	176	0.4	1.846	1.2
				1.758	1.1
S1 P (c)	271.20	206	0.5	1.948	1.2
				2.103	1.3
S1 P (d)	270.75	175	0.4	1.880	1.2
				1.978	1.2

Table 3 Mechanical results series 2 (P + F = whole stem, P = hemp hurds)

Reference	Mass (g) specimens 4 × 4 × 16 (cm)	Flexural strength (37 days)		Compressive strength (37 days)	
		Load (N)	Tensile (MPa)	Load (N)	Tensile (MPa)
S2 P + F (a)	298.4	202	0.5	1.890	1.2
				1.923	1.2
S2 P + F (b)	288.14	206	0.5	1.991	1.2
				2.015	1.3
S2 P + F (c)	293.61	260	0.6	1.984	1.2.
				2.132	1.3
S2 P + F (d)	304.08	278	0.7	2.064	1.3
				2.257	1.4
S2 P (a)	272.00	181	0.4	1.957	1.2
				1.746	1.1
S2 P (b)	287.13	209	0.5	1.841	1.2
				1.987	1.2
S2 P (c)	281.24	196	0.5	1.896	1.2
				1.973	1.2
S2 P (d)	287.78	186	0.4	1.822	1.1
				1.859	1.2

Conclusions

This paper addresses the feasibility of the implementation of an ancestral hemp variety against industrial hemp in concrete. In this context, the drying kinetics and stabilization with lime of earth mortars, mixed with water or plant infusions were studied for both hemp hurds and whole stem material. The results confirmed different findings with de-fibered and non-de-fibered stem material and also with different hemp varieties. Those differences could be due to anatomic and chemical deviations. However, the differences between both species are not important enough to disregard the use of Moroccan ancestral *C. sativa* L. - *indica* hemp for construction purposes. The research rather demonstrates that in hemp-clay concretes, stabilized with lime, different varieties of hemp may need different formulations containing appropriate clays, in order to obtain maximum performance. Adapted formulations and treatments seem to be necessary to optimize results in all hemp varieties and those are more important in de-fibered than in whole stem material. Furthermore, clay based concretes made with de-fibered and non-de-fibered hemp stem, stabilized with two different percentages of lime were compared. Concerning the mechanical properties, the lower results of compressive strength with higher amount of lime addition could be explained by the alkaline medium created by higher lime content which is probably the reason for higher hemi-cellulose release, causing hardening problems and hindering the interaction between clay and lime. This resulted in weakening of clay-lime matrix. Why a higher amount of lime addition benefitted the flexural strength of both concretes can only be explained through additional macroscopic studies, or preparing control specimens without addition of lime. Higher additions of lime didn’t reduce significantly the capillarity absorption and delayed the subsequent drying process of the specimens.

Acknowledgements The authors gratefully acknowledge the funding by REMINE Project, H2020-MSCA-RISE-2014 and Research groups HUM-629 and RNM 0179 (Regional Government of Andalusia). The authors thank to Antonio Sanchez Navas of University of Granada for technical assistance in analysis and the mineralogical X-ray diffraction of samples and also to Abdellatif Adebibe, whose request of collaboration in the alternative socioeconomic development of the Moroccan Central Rif region was an incentive for this research. Lime, hemp and clay materials were sponsored by members and collaborators of Cannabric (Spain) and Adrar Nouh (Morocco).

References

1. Ali, M., Liu, A., Sou, H., & Chouw, N. (2012). Mechanical and dynamic properties of coconut fibre reinforced concrete. *Construction and Building Materials, 30,* 814–825.
2. Amaducci, S., Scordia, D., Liu, F. H., Zhang, Q., Guo, H., Testa, G., et al. (2014). Key cultivation techniques for hemp in Europe and China. *Industrial Crops and Products*.

3. Anderson, L. C. (1974). A study of systematic wood anatomy in Cannabis. In *Botanical Museum Leaflets* (Vol. 24. pp. 29–36). Harvard University.
4. Arizzi, A., Cultrone, G., Brümmer, M., & Viles, H. (2015). A chemical, morphological and mineralogical study on the interaction between hemp hurds and aerial and natural hydraulic lime particles: Implications for mortar manufacturing. *Construction and Building Materials, 75,* 375–384.
5. Arizzi, A., Brümmer, M., Martín-Sanchez, I., Cultrone, G., & Viles, H. (2015b). 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*.
6. Arnaud, L., & Boyeux, B. (2011). La chènevotte comme nouveau Granulat écologique et performant pour une utilisation dans le bâtiment. Académie d'Agriculture de France – Séance du 12 Janvier.
7. Balčiūnasa, G., Vėjelisb, S., Vaitkusc, S., & Kairytėd, A. (2013). Physical properties and structure of composite made by using hemp hurds and different binding materials. *Procedia Engineering, 57,* 159–166.
8. Bevan, R., & Wooley, T. (2008). *Hemp lime construction: A guide to building with hemp-lime*. Bre-Press.
9. Biagiotti, J., Puglia, D., & Kenny, J. M. (2004). A review on natural fiber-based composites-part I: Structure, processing and properties of vegetable fibers. *Journal of Natural Fibers*.
10. Cérézo, V. (2005). Propriétés mécaniques, thermiques et acoustiques d'un matériau à base de particules végétales: approche expérimentale et modélisation théorique. L'Institut National des Sciences Appliquées de Lyon. L'Ecole Nationale des Travaux Publics de l'Etat, Thèse doctorale: Génie Civil.
11. Chen, T., Yao, S., Merlin, M., Mai, H., Qiu, Z., Hu, Y., et al. (2014). Identification of *Cannabis* fiber from the Astana Cemeteries, Xinjiang, China. *Economic Botany, 68*(1), 59–66.
12. Chouvy, P.-A., & Afsahi, K. (2014). Hashish revival in Morocco. *International Journal of Drug Policy, 25,* 416–423.
13. Crônier, D., Monties, B., & Chabbert, B. (2005). Structure and chemical composition of bast fibers isolated from developing hemp stem. *Journal of Agriculture and Food Chemistry, 53* (21), 89–8279.
14. De Bruijn, P. B. (2008). Hemp concretes: Mechanical properties using both shives and fibres. Faculty of Landscape Planning, Horticulture and Agricultural Sciences Alnarp.
15. De Bruijn, P. B., Jeppsson, K.-H., Sandin, K., & Nilsson, C. (2009). Mechanical properties of lime-hemp concrete containing shives and fibres. *Biosystems Engineering, 103*(4), 474–479.
16. Diquélou, Y., Gourlay, E., Arnaud, L., & Kurek, B. (2015). Impact of hemp shiv on cement setting and hardening: Influence of the extracted components from the aggregates and study of the interfaces with the inorganic matrix. *Cement & Concrete Composites, 55,* 112–121.
17. Elfordy, S., Lucas, F., Tancret, F., Scudeller, Y., & Goudet, L. (2008). Synthèse des connaissances sur les bétons et mortiers de chanvre. Construire en Chanvre.
18. Gourlay, E., & Arnaud, L. (2011). Des matières premières au béton de chanvre: optimisation des propriétés thermiques et mécaniques. 20ième Congrès Français de Mécanique Besançon.
19. Hustache Y., & Arnaud L. (2008). Synthèse des connaissances sur les bétons et mortiers de chanvre.
20. Ingrao, C., Lo Giudice, A., Bacenetti, J., Tricase, C., Dotelli, G., Fiala, M., et al. (2015). Energy and environmental assessment of industrial hemp for building applications: A review. *Renewable and Sustainable Energy Reviews, 51,* 29–42.
21. Ip, K., & Miller A. (2012). Life cycle greenhouse gas emissions of hemp–lime wall constructions in the UK University of Brighton, School of Environment and Technology, Cockcroft Building, Lewes Road, Brighton BN2 4GJ, United Kingdom.
22. Jiang, H., Wang, L., Merlin, M. D., Clarke, R. C., Pan, Y., Zhang, Y., et al. (2016). Ancient Cannabis Burial Shroud in a Central Eurasian Cemetery. *Economic Botany, 70*(3), 213–221.

23. Kymäläinen, H.-R., Hautala, M., Kuisma, R., & Pasila, A. (2001). Capillarity of flax/linseed (*Linum usitatissimum* L.) and fibre hemp (*Cannabis sativa* L.) straw fractions. *Industrial Crops and Products, 14*(1), 41–50.
24. Kymäläinen, H.-R., Koivula, M., Kuisma, R., Sjöberg, A.-M., & Pehkonen, A. (2004). Technologically indicative properties of straw fractions of flax, linseed (*Linum usitatissimum L.*) and fiber hemp (*Cannabis sativa L.*). *Bioresource Technology, 94*(1), 57–63.
25. Kymäläinen, H.-R., & Sjöberg, A. (2007). M. Flax and hemp fibers as raw materials for thermal insulations. *Building and Environment, 43*(2008), 1261–1269.
26. Nguyen, T., Picandet, V., Sofiane, A., & Baley, C. (2011). Influence of compactness and hemp hurd characteristics on the mechanical properties of lime and hemp concrete. *European Journal of Environmental and Civil Engineering,* 1039–1050.
27. Niyigena, C., Amziane, S., Chateauneuf, A., Arnaud, L., Bessette, L., & Collet, F. (2016). Variability of the mechanical properties of hemp concrete. *Materials Today Communications, 7*, 122–133.
28. Nozahic, V., Amziane, S., Torrent, G., Saïdi, K., & De Baynast, H. (2012). Design of green concrete made of plant-derived aggregates and a pumice–lime binder. *Cement & Concrete Composites, 34,* 231–241.
29. Sawler, J., Stout, J. M., Gardner, K. M., Hudson, D., Vidmar, J., & Butler L. (2015). The genetic structure of marijuana and hemp. *PlOS ONE, 10.*
30. Senga Kiessé, T., Ventura A., Van der Werf H. M. G., Cazacliu B., Idir R., & Andraina, A. (2016). Introducing economic actors and their possibilities for action in LCA using sensitivity analysis: Application to hemp-based insulation products for building applications. *Journal of Cleaner Production,* 1–12.
31. Silveira, D., Varum, H., & Costa, A. (2007). Análise do comportamentos sísmico de construções existentes em adobe. -7 Congresso de sismologia e engenharia sísmica. SÍSMICA.
32. Stevulova, N., Kidalova, L., Cigasova, J., Junak, J., Sicakova, A., & Terpakova, E. (2013). Lightweight composites containing hemp hurds. *Procedia Engineering, 65,* 69–74.
33. Struik, P. C., Amaducci, S., Bullard, M. J., Stutterheim, N. C., Venturi, G., & Cromack, H. T. H. (2000). Agronomy of fibre hemp (*Cannabis sativa* L.) in Europe. *Industrial Crops and Products, 11*(2–3), 107–118.
34. Van der Werf, H. G. M. (1994). *Crop physiology of fibre hemp (Cannabis sativa L.)* (Ph.D. thesis). Agricultural University, Wageningen, The Netherlands, p. 153.