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HEMP CONCRETE USING INNOVATIVE POZZOLANIC BINDER

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Abstract
The aim of the present study is to investigate the performances of hempcrete made of hemp shives and an innovative pozzolanic binder (slaked lime, metakaolin and admixtures). In order to improve the performances of hempcrete, a method of hemp shiv pretreatment, very simple and suitable with industrial production, was proposed. Mechanical and thermal properties of untreated and treated hempcrete samples were tested. The results show that hemp shiv pretreatment significantly improved the mechanical properties of hempcrete.

Keywords:
Hemp concrete, hempcrete, hemp shiv treatment

1 INTRODUCTION

In recent decades, in the construction domain, the innovative building materials, called eco-materials, have been developed. Numerous studies have been investigated the use of different fibres, woods and by-products issued from plants (e.g. wood, hemp, sunflower, flax, sisal) in building materials.

Plant aggregates, plant co-products in general, and hemp shives in particular, have been used to fabricate new materials for wall thermal insulation, which not only provide good thermal insulation, but also a limited impact on the environment and a low cost. Hemp shives are the ligneous particles extracted from hemp stems as a co-product of the process of hemp fibre extraction. They have been used to manufacture concrete with mineral binder. The thermal conductivity and hygrothermal behaviour of this concrete are not only compatible with its use as an insulating wall but could also lead to better energy performance due to their specific hygrothermal behavior [Samri 2008], [Tran Le 2010]. Nevertheless, some improvements are still needed to allow the large scale development of these kinds of materials. In fact, due to the high water absorption rate of plant aggregate, hempcrete requires an excessive amount of water at the time of mixing. This leads to a very long drying time, a decrease in mechanical strength and an increased risk of microbial proliferation. Pretreatment of the hemp shiv could be a solution to reduce its water absorption rate.

Finally, with regard to binder, hemp concrete using lime binder has been successfully studied by several authors [Nguyen 2010], [Arnaud 2012]. Magniont [Magniont 2010] has demonstrated the potential of flash calcined metakaolin and natural hydraulic lime NHL5 as a binder for hemp concrete. The mechanical and thermal properties of hempcrete using this binder are comparable to those found in the literatures.

A previous study [Dinh 2012] allowed the performances of innovative pozzolanic binder to be optimized. This paper aims to present the characterization of the mechanical and thermal properties of hemp concrete using pozzolanic binder and the benefits of pretreatment of hemp shives prior to its incorporation to the binder.

2 MATERIALS

2.1 Binder

In this study, an innovative pozzolanic binder designed in a previous work [Dinh 2012], called S binder, was used. Its ingredients are presented in Tab. 1.

Tab. 1: Composition of binder [Dinh 2012].

Component	MK	SL	Content by weight of MK and SL		
			SP	GC	K_2SO_4
Content (wt%)	70	30	1.6	0.5	3.0

MK = metakaolin, SL = slaked lime, GC = glycerol carbonate, SP = superplasticizer.

Metakaolin, MK, a pozzolanic addition, was a commercial product obtained from the Argeco Company in Toulouse, France. It is produced by flash calcination of kaolinite at 700°C and is composed of 51.4% of amorphous silicon-aluminates and 48.6% quartz [Trinh 2012]. The amorphous phase is responsible for the pozzolanic activity of MK, which

reacts with calcium hydroxide ($Ca(OH)_2$) to form C-S-H gel, calcium aluminate hydrates (C_4AH_{13} and C_3AH_6-hydrogarnet) and calcium alumino-silicate hydrates (C_2ASH_8-straelingite) [Frías 2001].

Slaked lime, SL, a commercial product from Calcinor, is obtained by the controlled slaking of quicklime with water. The major mineralogical ingredient, around 94%, is $Ca(OH)_2$.

Glycerol carbonate, GC, an organic admixture supplied by Huntsman, Spain, was used as a "safe" and environmentally friendly solvent. The benefits of GC incorporation into this innovative pozzolanic matrix have been presented elsewhere [Magniont 2010].

Superplasticizer, SP was used to reduce water content.

2.2 Plant aggregates

The plant aggregate used in this study was hemp shiv, the ligneous particles extracted from hemp stems as a co-product of the process of hemp fibre extraction. In this study, the hemp shiv was provided by the Agrofibre company in Cazères (Haute-Garonne, France). Hemp shiv is obtained through an industrial defibration process by mechanical breaking, after which particles are dusted and calibrated. Hemp shiv particles (Fig. 1) are beige to white, elongated, plane parallel shapes 1–3 mm thick and 5–25 mm long.

Fig. 1: Hemp shiv particles

In a previous study [Dinh 2013], the characterization of hemp aggregates was presented. Their bulk density and thermal conductivity were shown in Tab. 2 which are within range of values found in the literature. For the water absorption, dry hemp shiv absorbed around three times its weight (325%) after 48 hours with very fast absorption kinetics during the first minute (198% - around 60% of the final value).

Tab. 2: Bulk density and Thermal conductivity of hemp shiv [Dinh 2013].

Measure origin	Bulk density (kg/m^3)	λ (W/ (m .k))
[Dinh 2013]	111.8 ± 0.2	0.0578 ± 0.0004
[Cerezo 2005]	110 and 155	0.048 and 0.058
[Magniont 2010]	134.8	0.055
[Verdier 2012]	148.3 ± 1.9	0.056 ± 0.0002

3 METHODS

3.1 Water absorption of hemp shiv

The water absorption capacity of hemp shives was determined on three samples based on current work of TC Bio-aggregates based building materials of the RILEM. The dry samples were immersed in water in a synthetic permeable bag and the gain in mass was measured after 1, 15, 240 minutes, and 48 hours. Before each weighting, the material was quickly dried with a salad spinner (in 50 seconds – two rounds per second). The aim of this step was to eliminate the water adsorbed at the surface of plant particles or located among them.

This test was carried out for normal and pretreated hemp particles. The quantity of each natural sample is around 25g, and that of pretreated hemp shiv sample is around 60g obtained from around 25g of natural hemp shiv. A balance accurate to 0.01g and a salad spinner (25 cm in diameter and 20 cm in height) were used. The water absorption capacity of each sample was evaluated by the equation (1)

$$W = \frac{M_t - M_0}{M_0}.100\% \quad (1)$$

W: Water absorption capacity (%), M_0: Mass of dry sample (g), M_t: Mass of sample after each immersion time (g)

3.2 Hemp shiv pretreatment

Hemp shives were pretreated for 2 days before being used to make hempcrete samples. The pretreatment employed the binder concerned in the fabrication of the hempcrete. For each cubic metre of hempcrete, hemp shives were pretreated with a binder paste with a water to binder ratio (W/B) and a hemp shives to binder ratio (S/B) of respectively 1 and 1.5, as presented in Tab. *3*3. The pretreatment process consisted of putting the hemp shives into a mixer and mixing for 2 minutes, then gradually introducing the water and mixing for 5 minutes to wet the hemp particles, before adding the binder and mixing the whole for a further 2 minutes. Finally, the treated hemp shives were conserved for 2 days according to two modes: keeping them in tight plastic bags (SP1) or putting them on the waterproof floor of indoor room in 5 cm thickness (SP2).

Tab. 3: Pretreatment formulation of hemp aggregates for 1 m^3 of hempcrete

Hemp shiv (kg)	Pozzolanic binder (kg)	Water (kg)	W/B	S/B
161.9	106.85	106.85	1	1.5

3.3 Fabrication of hemp concrete samples

The formulations of hempcretes are shown in Tab. 4.

Tab. 4: Quantity of components for 1 m^3 hempcrete

Mixture	Binder (kg)	Hemp shiv (kg)	Water (kg)	S/B	W/B	ρ_f (kg/m^3)
S	374.35	161.90	302.75	0.43	0.81	839.0
SP1 SP2	374.35	161.90	302.75	0.43	0.81	839.0

S/B and W/B: hemp shiv and water to binder ratios
ρ_f: fresh density of hempcrete

The mixing processes for hempcrete and pretreated hemp shives are presented in Tab. *54* 5. For the conservation, all the hempcrete samples were conserved in the moulds in the humid room at 20°C and more than 95% RH during 48 hours. After that time, all these samples were conserved in the climatic room at 20°C and 65% RH until the date of the test. Samples were conserved with or without moulds depending on different tests, as present in Tab. 6.

Tab. 54: Process of mixing for hempcrete

Hempcrete with untreated shives	Hempcrete with pretreated shives
1. Mix hemp shives for 2 minutes	1. Introduce pretreated shives and binder into mixer, mix for 2 minutes
2. Introduce water to wet hemp shiv, mix for 5 minutes	2. Introduce mixing water, mix for 5 minutes
3. Introduce binder, mix for 2 minutes	3. Obtain a homogeneous mixture
4. Introduce mixing water, mix for 5 minutes	
5. Obtain a homogeneous mixture	

Tab. 6: Conservation form of hempcrete at 20°C and 65%RH after 2-day age.

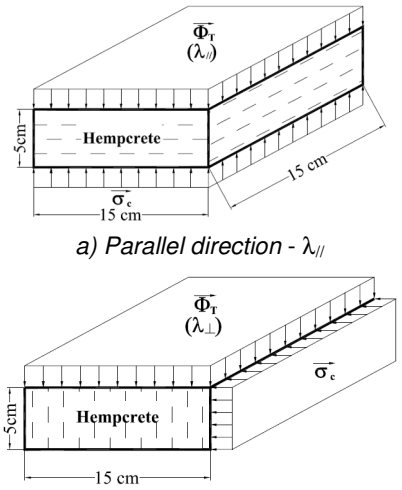
Order	Test	2 to 7 days	After 7 days
1	Thermal conductivity	without mould	without mould
2	Compressive test	Conservation in mould without top and bottom	without mould

For the compressive test, the samples were fabricated in the form of cylinders (16 cm in diameter and 32 cm high) by Vibrocompression machine using a compaction pressure of 0.6 MPa with vibration time of 30 seconds. For the thermal conductivity test, two kinds of hard moulds were used to cast samples in order to test them according to parallel and perpendicular directions with the compaction direction: horizontal parallelepiped moulds with 15 x 15 cm^2 section and 5 cm in height, and vertical parallelepiped with 15 x 5 cm^2 section and 15 cm in height. Manual compaction was applied. All the samples had the same fresh density.

3.4 Hempcrete tests

The compressive tests were realised on the cylindrical samples at 28 days of age. The device used was the HOUNSFIELD H50KS machine (load cell capacity: 50 kN) with a constant displacement rate of 5 mm/minute. The young's modulus of hempcrete was determined from the results of compressive test. It was determined as the slope of the stress strain curve within elastic region, in which the stress strain curve of hempcrete obeys Hook's Law.

Thermal conductivity tests were performed using a hot plate method for both dry and humid state (humid state: in equilibrium with ambient air at 20°C and 65% RH). Before the test, the samples must reach the stable mass state in which the change in mass was less than 0.1% between two weightings 24 hours apart. Measurements were made at 25°C with a difference of temperature of 15K between the two plates. The steady state was assumed to be reached when the change in conductivity is less than 1% in 90 minutes. This test was measured according to parallel and perpendicular directions with the compaction direction. Fig. 2 describes the compaction direction (σ_c) and the heat flux (Φ_T). In Fig. 2a, the heat flux is parallel to the compaction direction, the thermal conductivity value is noted $\lambda_{//}$. In Fig. b, the heat flux is perpendicular to the compaction direction, the thermal conductivity value is noted $\lambda_{\perp}$.



a) Parallel direction - $\lambda_{//}$

b) Perpendicular direction - $\lambda_{\perp}$

Fig. 2: Directions of compaction and heat flux

4 RESULTS

4.1 Water absorption of treated hemp shives

The water absorption capacity of the treated sample (SP2) was compared with that of the untreated hemp shiv sample – noted "Normal". In order to compare the water absorption capacity between treated and untreated hemp shives, the water absorption capacity of treated hemp shives was relatively calculated according to the initial mass of untreated hemp shives; therefore, M_t and M_o in equation (1) in section 3.1 were calculated by equations (2) and (3) assuming that the water absorption rate of the paste is negligible when compared to the one of hemp shiv.

$$M_t = M_{t1} - M_p \quad (2)$$

$$M_0 = M_{01} - M_p \quad (3)$$

M_{t1}: mass of treated hemp particles after each immersion time containing enclosed paste mass (g), M_p: mass of enclosed paste used to treat hemp particles (g), M_{01}: mass of dry sample before immersion (g)

The results are shown in Fig.. This figure shows the water absorption capacity of treated shives in comparison with the normal shives. After 48 hours, the water absorption of treated hemp shives was notably lower in comparison with that of non-pretreated shives. Indeed, it absorbed around 204% in mass, which reduced 27% in comparison with the non-pretreated shives. During the first minute, the pretreated shives absorbed only 44% in mass (around 20% of the final value), which decreased 65% in comparison with the untreated hemp shives. In accordance with the results of water absorption in previous studies [Nozahic 2012a and Dinh 2013], the absorption kinetics of both untreated and treated shives conforms to logarithmic function of time (W_N and W_{SP2}). These Two logarithmic functions indicate that the absorption coefficient of treated shives (SP2) is equivalent to that of untreated shives. Nevertheless, the initial water adsorption of SP2 shives is much lower than that of untreated shives. This demonstrates that the coating of hemp particles with a mineral binder with much lower porosity significantly reduced the water absorbed in the first minute by the hemp shives, and therefore limited their water absorption capacity.

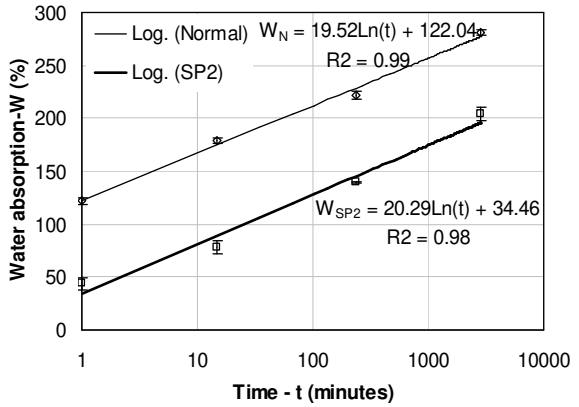


Fig. 3: Water absorption of hemp shives according to logarithmic function of time.

These results confirm the high water absorption and retention capacity of hemp shiv, attributed to their high porosity and capillary structure in previous studies [Arnaud 2012], [Nozahic 2012].

Several studies showed a significant reduction of water absorption of treated plant particles in general, and hemp particles in particular in comparison with the non-treated plant aggregates (this reduction ranged from 25 to 70%) [Khazma 2008, Monreal 2008, Monreal 2011, Nozahic 2012]. However, in these studies, plant aggregates were treated by different matters (linseed oil, cement and sucrose) and conserved from 21 to 28 days before their use. In comparison with these studies, our results are similar, but our method of pretreatment is simpler and easily reproducible at industrial scale. This may be promising for the improvement of hempcrete properties using treated hemp shives.

4.2 Mechanical behaviour of untreated hempcrete

The mechanical behaviour of untreated hempcretes was characterized by the compressive test realized on the S hempcrete samples at 28 days. The mechanical behaviour of the hempcretes is presented in Fig. 4 and Fig. 5 below.

Zone I Zone II Zone III Zone IV

Fig. 4: Failure stages of hempcrete at 28 days.

Fig. 4 shows the failure stages of a hempcrete sample during the compressive test at 28 days. This observation indicated that in zone I, hempcrete sample presented a homogeneous material without fissure. In zone II, although it is very difficult to observe the fissure at the surface level of the samples, the horizontal deformation can be visible at the end of this phase. In zone III, the horizontal deformation of sample clearly increased, some small fissures were observed at the end of this phase, but the samples were not completely ruptured. In zone IV, the samples were totally ruptured.

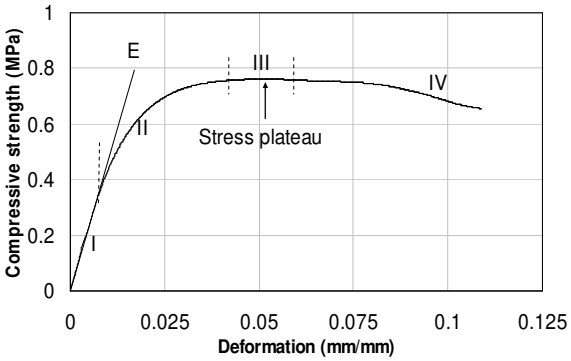


Fig. 5: Compressive test of S hempcrete at 28 days.

Fig. clearly shows that the mechanical performance of S hempcrete presented four zones. In Zone I, the mechanical behavior presented as a linear elastic material, which performed as a homogeneous material. In this phase, the stress-strain curve is a linear line with the smallest deformation zone (form 0 to 1%). This result was in accordance with the results in literature [Cerezo 2005 & Nguyen 2010]. In Zone II, the material showed an elastic-plastic behavior, which was found in Nguyen's study [NGU10] and similar to the beginning of pre-peak phase in Cerezo's study [CER05]. The stress-strain curve is a continuous flexural curve. This phase exhibited larger deformation zone and slower increase of strength in comparison with those of zone I. This phenomenon can be attributed to the fact that the matrix and/or the interface between the hemp particles and the binder were progressively ruptured. The compressive strength of hempcrete reached maximum value at the end point of this phase (0.77 MPa). In Zone III, the mechanical behavior of S hempcrete was the stress plateau state with the maximum stress value. This behavior can be attributed to the distribution of the stress into the hemp particles and to the complete destruction of matrix; moreover, the stress during fabrication of hempcrete could also contribute to strength of hempcrete in this phase [Nguyen 2010]. Zone IV presented the complete destructive phase of hempcrete.

In Fig. , the E line exhibits the linear relation of the stress strain curve in zone I from the origin point of coordinate, which means that zone I of the stress strain curve of S hempcrete obeys Hooke's Law. Thus, elastic modulus of S hempcrete was determined by the slope in the elastic region of the stress strain curve (modulus: 46.79 MPa).

In comparison with previous studies, our results illustrated that the mechanical behaviour of our untreated hempcrete were around 3 times higher than the values according to the recommendations of French Building Confederation (FBC) for hempcrete [Association 2007] and similar with other results with the same dry density [Arnaud 2012, Cerezo 2005, Mounanga 2009 and Nozahic 2012].

4.3 Mechanical behaviour of treated hempcrete

To evaluate the influence of the treatment of hemp shives on the mechanical behavior of hempcrete, compressive tests were performed on two kinds of mixtures using treated hemp shives (SP1 & SP2) with the same fresh density of S hempcrete at 28 days. The results are shown in Fig. 6 and Tab. below.

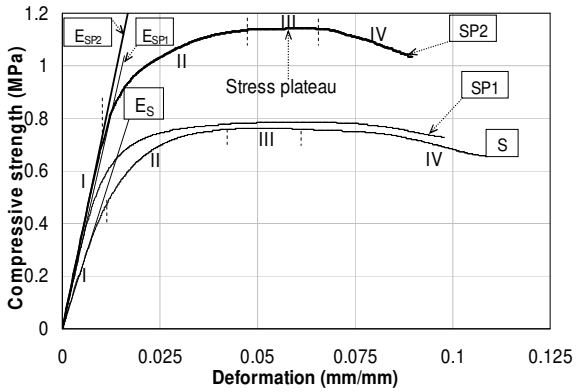


Fig. 6: Compressive test of SP1 & SP2 hempcretes at 28 days.

Fig. 6 shows the mechanical behaviours of two kinds of treated hempcretes (SP1 & SP2) in comparison with those of untreated hempcrete (S). It can be seen that the behaviours of SP1 and SP2 hempcretes are similar to S hempcrete (4 zones). We remarked that although its modulus was significantly higher than that of S hempcrete, the maximum compressive strength of SP1 hempcrete was just slightly higher (around 3%), (Tab. 7). We can conclude to an insignificant efficiency of SP1 treatment of hemp shives on the mechanical performance at 28 days. However, this conservation method of treated hemp shives before mixing was not convenient for the hempcrete production in the large scale because the treated hemp shives were conserved in tight plastic bags. For SP2 hempcrete, the maximum compressive strength and modulus are much higher than those of S hempcrete (around 1.5 times higher, Tab.). This demonstrated a significant efficiency of SP2 treated hemp shives on the mechanical performance at 28 days. On the other hand, the conservation method of SP2 treated hemp shives before mixing was much simpler in comparison with that of SP1 treated hemp shives; therefore, it is very convenient for the hempcrete production in the large scale.

Tab. 7: Compressive strength and elastic modulus of treated hempcretes at 28 days.

Mixture	ρ_f (kg/m^3)	ρ_{28} (kg/m^3)	σ_{max} (MPa)	E (MPa)
S	839.0	597.2	0.77 ± 0.01	46.79 ± 0.11
SP1	839.0	604.5	0.79 ± 0.05	64.91 ± 0.15
SP2	839.0	585.2	1.14	71.69

In conclusion, the results of the mechanical behaviours of pozzolanic hempcretes demonstrated that SP2 hempcrete has the best mechanical properties. This treatment method is also a simpler method of hemp shiv pre-treatment than previous studies. Thus, we can conclude that SP2 hempcrete formulation can be applied for industrial production.

4.4 Thermal conductivity

The thermal conductivity of hempcrete was measured according to parallel direction ($\lambda_{//}$) and perpendicular direction ($\lambda_{\perp}$) with the compaction direction for both untreated and treated hempcretes. The measurements were performed on the 5-cm-thick samples. The results are presented in Tab. and Fig. 7.

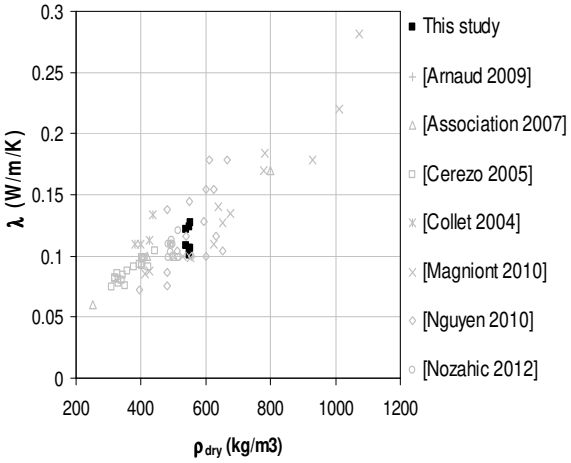


Fig. 7 Thermal conductivity of dry hempcretes vs dry density.

The results in Tab. show low thermal conductivity of hempcrete samples, which is suitable for a self-insulating material. These measurements confirmed the insignificant influence of hemp shiv treatment on the thermal conductivity of hempcrete. In regard to the influence of relative humidity, the thermal conductivity of hempcrete samples conserved at 65% RH condition was slightly higher (from 1.01 to 1.1 times) than that of dry hempcrete samples. This study was also consistent with the studies in literature [Arnaud 2009, Bruijn 2013, Evrard 2008, Magniont 2010 & Samri 2008]. On the other hand, these results also confirmed the difference of thermal conductivity of hempcretes between two directions ($\lambda_{\perp}$ and $\lambda_{//}$). The $\lambda_{\perp}$ to $\lambda_{//}$ ratio was from 1.13 to 1.19 for dry hempcretes and from 1.15 to 1.17 for humid hempcretes (Tab.), which confirmed the influence of compaction direction on the thermal conductivity of hempcretes being consistent with previous studies [Nguyen 2010, Nozahic 2012a, Picandet 2011]. In comparison with the measurements in previous studies, we remarked that our results are within the range of values found in the literature, as synthesized in Fig. 7.

In conclusion, the thermal conductivity of our hempcretes is in the range of the values found in the literature and is not significantly affected by the treatment of hemp shives

Tab.8: Thermal conductivity hempcretes.

Samples	ρ_{dry} (kg/m^3)	ρ_{90} (kg/m^3)	Dry state			Humid state		
			$\lambda_{\perp}$ (W/m/K)	$\lambda_{//}$ (W/m/K)	$\lambda_{\perp}/\lambda_{//}$	$\lambda_{\perp}$ (W/m/K)	$\lambda_{//}$ (W/m/K)	$\lambda_{\perp}/\lambda_{//}$
S	539.9	556.0	0.122 ± 0.002	0.108 ± 0.001	1.13	0.132	0.115	1.15
SP1	552.6	560.0	0.127 ± 0.002	0.106 ± 0.001	1.19	0.137	0.117	1.17
SP2	549.7	557.2	-	0.101	-	-	-	-

5 CONCLUSION

This study presents a new treatment method of hemp particles, and the mechanical and thermal performance of hempcrete made from untreated and treated hemp shives and innovative pozzolanic binder. Our treatment method of hemp aggregates was much simpler than that of previous studies and suitable for industrial production of hempcrete in large scale thanks to easy treatment and short time of conservation. Moreover, the significant reduction of water absorption capacity of our treated shives can compare with that of treated plant aggregates presented in literature. Concerning mechanical behaviour, the results of the compressive test and the Young's modulus of hempcrete demonstrate that the mechanical performance of hempcrete made from treated hemp shives is significantly better than that of the mix using hemp shives without pre-treatment, especially SP2 hempcrete. As regards thermal performance, the measurement of thermal conductivity confirms that the treatment of hemp shiv proposed does not affect significantly the thermal conductivity of hempcrete. Thus, our hempcrete can be used as self-insulating building materials. These hempcretes can be considered as potential material for the production of prefabricated blocks for construction.

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