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Physical properties of Australian hurd used as aggregate for hemp concrete

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ABSTRACT

The purpose of this study is to determine the key properties of Australian hemp particles which are used for manufacturing hempcrete. Hemp characteristics have a wide variability due to the influence of the environment conditions in various farmed areas. This study focuses on the measurements of the mechanical, thermal and acoustic performances of three Australian hemp: unretted hemp hurd, retted hemp hurd, and hemp fines. Hemp hurd is usually used in non-load bearing building walls, and hemp fine, which is the by-product of hemp manufacturing industry, is usually incorporated into a render. The experimental results show that the main impact of the retting process is a decrease in bulk density and leading to an improvement in thermal and acoustic properties. Without compaction, the bulk density is ranged from 97 and 118.8 kg.m^{-3}, the max sound absorption coefficient from 0.88 and 0.99, and the thermal conductivity from 64 to 97 mW.m^{-1}. K^{-1}. Hemp fines have excellent thermal and acoustic properties and appear to be an efficient aggregate to produce an insulating render. Australian hemps investigated in this study have shown very similar characteristics to European hemps.

1. Introduction

Recycling materials in building and infrastructures has an important role to reduce the carbon footprint of the construction industry. Bio-based materials, derived from plant sources, have become increasingly popular to produce eco-friendly materials with a low carbon footprint. In fact, bio-based materials made from renewable vegetable granulates allow carbon storage during growth [1,2]. Among these materials, hemp concrete or hempcrete becomes more and more popular in construction because of its manufacturing from renewable resources (plants), and its non-degradable characteristics over time [3–6]. Hempcrete is generally composed of hemp shiv, woody core parts of the hemp stalk, binder (lime based cementitious) and water. Depending on the mix design, hempcrete can be used as bricks, a coating/spraying layer or as a filling material for wall components [7,8]. In comparison with conventional building materials, the other advantages of hempcrete are its lower density, good acoustic properties [9–12], excellent moisture buffer capacity [13], and good thermal insulation properties [14–18].

In Europe, several studies have been conducted investigating the mechanical, thermal and acoustic properties hemp and hempcrete [19]. The hemp characteristics impact the acoustic [20], thermal [21] and mechanical properties [22] of hempcrete. A fine characterisation of the hemp in bulk state enables to improve the mix design and casting process of hempcrete. In Australia, the application of hemp as a construction material has just started. Only few studies [23,24] reported the complete characteristics of hemp farmed in this country. This paper focuses on the determination of the main features of different types of hemp grown in New South Wales (Australia). In particular, the influence of the retting process was investigated.

2. Background

The main parameters influencing hempcrete properties [20,25,26] are the characteristics of the hemp (particle size distribution, water absorption, initial water content and dry density), the type of binders (lime, lime based cementitious, prompt natural cement), type of additives and the manufacturing method (compaction energy and molding method). The bulk density of dried hemp varies from 70 to 160 kg.m^{-3} [25]. The density of hemp concrete depends on the mix design, the size

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and the porosity of aggregates and the energy of compaction. Cerezo [20] tested ten formulations with different binders and hemp/binder ratios and found a final average density ranging from 455 to 782 kg.m^{-3}. For a hemp/binder mass ratio of 0.15, Mazhoud [17], with hemp lime plasters, and Viel [22], with bio-binders, obtained an average value ranging from 715 to 895 kg.m^{-3} and 176–273 kg.m^{-3}, respectively. Mechanically, hempcrete has a very ductile elasto-plastic behaviour in both compression and tension because of the low rigidity of the particles. The drying conditions and the age of hempcrete have a great influence on the mechanical behaviour [27]. Nguyen [26] measured compressive strengths after 28 days ranging between 0.2 and 3.6 MPa, for an ultimate strain equal to 7.5 %. Young's modulus values have also high variability and there are different methods for its assessment. Cérézo [20] found a Young's modulus ranging from 1 to 3 MPa for low binder content, 32–95 MPa for intermediate dosages and 100–160 MPa for high dosage when considering the slope at the origin of the strength-strain curve. Compaction [28] and layering during batching of hempcrete specimens also affect the internal structure of the material, which cause a directionally dependant [29]. A higher compaction level leads to an increase of the compressive strength [30].

The acoustic comfort depends on the reverberation time in the room, which is directly affected by the sound absorption coefficient of the materials [31] (and the volume of the room and the different room surfaces). A higher sound absorption coefficient results in a lower reverberation time. Hempcrete has a high porosity of about 70–80 % [27] due to the macropores or interparticle pores between the particles of hemp shiv, the mesopores within shiv and binder and micropores in the binder. Its porous structure enables sound absorption where the sound wave is dissipated within the material's pores via conversion to heat [32]. The Noise Reduction Coefficient (NRC) is the arithmetic average of the absorption coefficients determined at the octave band of 250 Hz, 500 Hz, 1000 Hz and 2000 Hz. The measure is usually carried out with an impedance tube on small sample. Hemp fibers have a NRC of about 0.4 for a sample of 30 mm thickness, 100 mm diameter and a density of 50 kg.m^{-3} [33]. Hempcrete exhibits a sound absorption coefficient of about 0.6 [20] depending on the binder type, the compaction process, the frequency (sample thickness between 100 and 300 mm and a bulk density of about 400 kg.m^{-3}). Fast setting cement binder displays significant lower sound absorption capabilities than hydraulic lime binders [11].

Regarding the hydric properties of hemp shiv, as a result of its very porous structure with a total porosity (about 70–80 %) very close to the open porosity [34], is a high K_1 (Eq. 2) water absorption coefficient (about 50). The initial water absorption (1 min immersion) can range from 112 to 243 % with a final water content (48 h immersion) ranging between 293 and 433 % [25,36]. Therefore, hempcrete enables an absorption of large quantities of water [35]. Hempcrete has a high vapour permeability ranging between 10.10^{-11} and 10.10^{-10} kg. m^{-1}.s^{-1}. Pa^{-1}. According to Evrard [37], when the mass variation is less than 1 % over 24 h, equilibrium is considered to be reached. Only a few days up to more than 15 days to reach the equilibrium for small broken samples of hempcrete, which is a very short time. Consequently, hempcrete presents a very good humidity regulation capacity, with a moisture buffer value around 2.15 g.m^{-2}.%RH^{-1}, and helps to maintain the building hygrothermal comfort [14].

Concerning the thermal conductivity, Arnaud [38] reported that the thermal properties of hempcrete are very sensitive to water vapour and shows a drastic increase when relative humidity (RH) increases. The bulk density has also a major effect; the lower is the density, the lower is the thermal conductivity [39,40]. The thermal conductivity of hempcrete ranges between 0.11 W.m^{-1}. K^{-1} for dry samples and 0.32 W.m^{-1}. K^{-1} for samples at 100 % RH and, for not compacted hemp shiv, between 0.05 and 0.1 W.m^{-1}. K^{-1} [39]. Evrard [37] found that, for a wall mix of lime hemp concrete, the thermal conductivity was 0.08 W.m^{-1}. K^{-1} for dry samples and 0.13 W.m^{-1}. K^{-1} for samples conditioned at 40 % RH. The specific heat capacity is 1.4 kJ.kg^{-1}. K^{-1}, and its thermal diffusivity is 0.14 mm^2.s^{-1}.

Hempcrete has a potential to delay temperature elevation within building elements and delay fire spreads. Due to capillary condensation, moisture transfer occurs by mechanisms of condensation and evaporation of vapour thanks to the high water permeability of hempcrete [40]. This is likely due to the latent heat of the water (moisture) contained within hempcrete that undergoes a phase change from water bound in the binder to steam (low increase of temperature up to 70 − 80 °C). Once all the water is evaporated, the local temperature increases rapidly to match that of the environment and any isolation properties of the hempcrete are lost. In case of a use of a lime based binder, the reaction of the lime between 900–1000 °C is expected to complete the lime cycle and the hydraulic lime is turned into limestone (calcium carbonate) that holds the charred hemp wood together in a brittle configuration. Since the phase changes occur at different times, the increase in temperature into the protected structure is delayed [41,24].

3. Raw materials

Australian hemp used was farmed in the Dungog region in the Hunter Valley (New South Wales). A late flowering low THC (psychoactive component tetrahydrocannabinol) variety, called Frog One [42], was considered. It was developed as a dual-purpose variety from new genetic material through hybridization of 12 landraces in a breeding program conducted in southern NSW between 1997 and 2000. It is a dioecious variety for production of both seed and fibre. It can be continuously cropped for fibre from August through to March and planted for grain in February to March for harvest in June to July. The decortication process is accomplished by a hemp decorticator machine, which separates the shive (by-product) and the bast fiber (automotive and textile industries). The shives were packed in bags of 10 kg and were sampled according to the protocol in the Ref. [43]. Three different hemps, with different retting and manufacturing processes, were studied (Fig. 1). The retting process involves the extraction of bast fibre from the harvested stem [44]. This progression is completed either by microorganisms present on the stems or in soil, acid/bases, or by special enzymes. Three major types of retting can be distinguished including field (or dew), water and chemical retting. The last two require special facilities (tanks, dryers, specialty chemicals). Dew retting is accomplished by leaving harvested hemp stalks on the ground for several weeks (2–10 weeks). The duration of the retting process depends on the availability of moisture and air temperature. Warm weather with intermittent precipitation maintaining moisture within the hemp stalks supports microbial activity and accelerates the process of pectin degradation. Hurd (or shiv) and bast fibres in properly retted stems separate easily at breaking and bast fibres form characteristic bands. Thus, a variability factor of hemp characteristics is the dew retting process, which depends on environmental factors such as temperature, moisture, duration. For the hemp used in this study, the retting process consisted of a dew retting of roughly 6 weeks. The tested samples are the following:

- Sample H-S-UR: Unretted small chop hemp hurd.
- Sample H-S-R: Retted smaller chop hemp hurd.
- Sample H-F: Hemp fines

Hemp hurd is mostly mixed with a binder and used as a filling material into timber walls frame. Hemp fines are very small pieces of hemp hurd mixed with some very short bast that are a by-product of hemp manufacturing process. There is also dust, which is largely separated out. They are incorporated in a render like as aggregate.

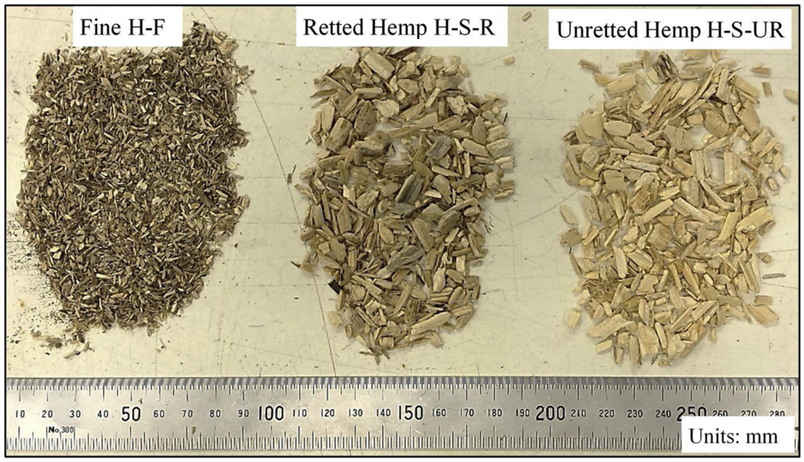

Fig. 1. Tested hemp samples.

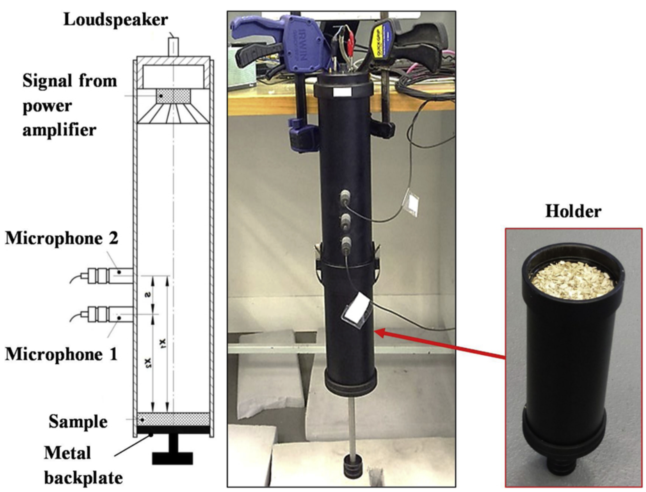

Fig. 2. Experimental setup for the impedance tube system.

4. Procedures

4.1. Bulk density

Tests were conducted according to the procedure in Ref. [43] with dried specimens. The dimensions of the glass cylindrical mould used are 280 mm height and 150 mm diameter and the maximum particle size is lower than 10 mm. The coefficient of variation of the results was always lower than 5 %.

4.2. Raw material water content and water absorption

Tests were conducted according to the protocol in Ref. [43]. The raw material water content, which represent the quantity of water of the packed shiv, is calculated with Eq. 1. The hemp was dried in an electric furnace at 60 °C until the mass of dried hemp doesn't change more than 0.1 % over 24 h. Metallic square mesh bags with 1 mm^2 perforation were used to determine the water content by immersion for different duration. The water content was calculated with Eq. (1). The Initial Water Content (IWC) represent the external water absorption of the shiv surface for the first minute (Eq. (2)). The Final Water Content (FWC) is the water content after 48 h of immersion. K_1 is the diffusion rate of the water in the shiv cells.

$$W(t) = \frac{m(t) - m_D}{m_D} \tag{1}$$

Where W(t) is the water absorption ratio at time t, m_D is the initial oven-dried aggregate mass, m(t) is the soaked hemp shiv aggregate mass after time (t)

$$W(t) = IWC + K_1 . \log(t) \tag{2}$$

Where IWC is the Initial Water Content and K_1 is water absorption coefficient (slope of the curve).

4.3. Particle size distribution

The particle size distribution is analysed by a sieving according to the protocol in Ref. [43]. The sieving was carried out using a mechanical shaker. The nominal opening sizes of the 200 mm diameter sieves are 4.75, 2.36, 1.18, 0.60, 0.425 mm. The dust content is considered in the total mass of the material with a diameter lower than 0.5 mm.

4.4. Acoustic properties

The sound absorption measurements were performed using a two-microphone impedance tube B&K type 4206 [45,46] based on the transfer-function method [47]. The measurement is carried out following the ISO 10534-2 standard [48]. The inner diameter of the tube is 100 mm and the spacing between the two microphones position is 100 mm. The tube was positioned in a vertical position (Fig. 2) to allow the filling of the holder with the shiv [49,50,33]. The samples were placed at the top of the tube and held in place by a rigid blackplate. At the other end, a loudspeaker fed white noise into the tube to provide equal sound energy per constant bandwidth per Hertz. The incident sound, from the loudspeaker, and the reflected sound from the sample were recorded by two microphones positioned at two different locations. An analyser (NI 9234 CompactDAQ 24 bit) generates the source signal and records the measured data. The signals were post processed to obtain the auto and cross-spectra required to produce the transfer function. Then, the absorption coefficient was calculated based on the transfer-function method. Depending on the tube diameter and the spacing between the two microphones position, the frequency range was between 50 Hz and 1600 Hz.

The sample thickness was 50 mm [51] and three tests with three different samples were performed. For the experiments with the shiv, dried samples were used with two different compaction levels: without compaction and a compaction that leads to 30 % increase of the bulk density (indexed by H). The compaction process is a hand compaction to fill the container with the required quantity. Each test were repeated 3 times with 3 different samples to access the reproducibility of the results.

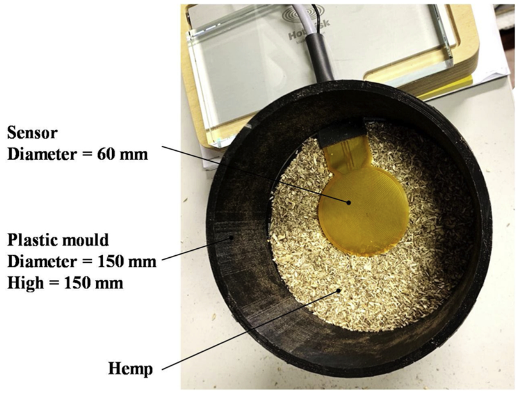

Fig. 3. Experimental setup for the thermal tests (Hot Disk system) with a half filled mould.

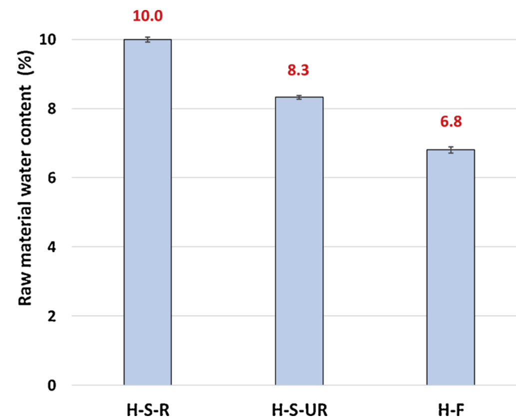

Fig. 4. Raw material water content of the packed hemp samples before drying.

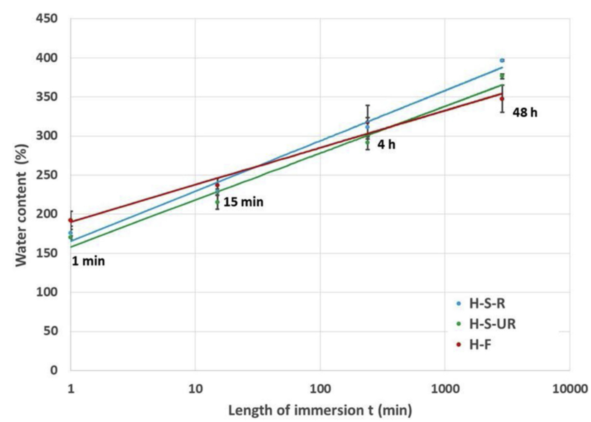

Fig. 5. Water content after different immersion times for dried hemp samples.

4.5. Thermal properties

Tests were conducted with a transient plane source technique [52] (Hot Disk system). A thin metal disk acts as a continuous plane heat source and simultaneously as a resistive temperature sensor. By monitoring the resistance of the sensor which reflects the temperature variations during the heating period, the thermal properties of the surrounding metal film can be extracted. Indeed, the tested material is sensitive to the temperature profile during the heating period of the sensor [53]. This technique enables to measure the thermal conductivity, the thermal diffusivity and the specific heat.

Tests with shiv were performed according to the procedure in Ref. [43]. Dried samples with the same levels of compaction as acoustic tests were tested. A Plastic cylindrical mould with 150 mm height and 150 mm diameter was used (Fig. 3). The diameter of the sensor was 60 mm, the measurement time was 320 s and the thermal power was ranging between 100 and 250 mW. For each sample, test was repeated 7 times and the coefficient of variation of the results was always lower than 5 %.

5. Results and discussions

The main results of the mechanical, thermal and acoustic tests are reported in Table 1

5.1. Water content, bulk density and particle size distribution

The water content of the packed supplied raw materials are depicted on Fig. 4. During the retting process, the hemp stalks are left outdoor in the field for 6 weeks, which means that the water content can vary following the weather condition. For the supplied hemp, the water content of the retted hurd was about 20 % higher than the unretted one. After drying, the retting process or the particle size have no significant influence on the water absorption for all immersion times as shown on Fig. 5. Due to a high porosity of the material, with a K_1 water absorption coefficient around 57 and a water content around 171 % after 1 min, the water absorption is very fast. Batching process will have to be adapted to minimize the effect of this high water absorption capacity. For the hempcrete mix process, this phenomenon involves, a brief water pre-wetting (around 1 min) of the shiv following by the addition of the binder in order to have enough water for its hydration.

Fig. 6 gives the results for the bulk density in dry state. The retting process causes a 12 % decrease of the bulk density, which is explained by the degradation of the hemp. This result is confirmed by Ribeiro et al. [54] who noticed a linear decrease of the stalk density regardless of the retting process. The volume solid fraction was calculated in considering a shiv cell wall density of 1450 kg.m^{-3} (holocellulose density). The values obtained for retted and unretted hemp are, respectively, 7.2 and 8.2 %. The low proportion of the solid fraction is mainly due to the high porosity of the material. The particle size distribution and the dust content (particle size lower than 0.5 mm) are depicted on Fig. 7. The results are quite similar for retted and unretted hemp. The hemp fines (H-F) show that a higher material finesse leads to a lower bulk density.

Table 1
Overview of the main results.

Sample	Passing 4.75 mm (%)	Dust (%)	BD (kg. m^{-3})	IWC (%)	FWC (%)	K_1	Max sound absorption coefficient$^{(*)}$	Thermal conductivity$^{(*)}$ (mW. m^{-1}. K^{-1})
H-S-R	81.5	0.2	104.6	165.3	387.8	64.3	0.92 - 0.98	79 - 100
H-S-UR	79.0	0.0	118.8	158.3	365.6	59.9	0.88 - 0.98	97 - 115
H-F	99.6	25.0	97.0	190.3	354.4	47.4	0.99 – 0.86	64 - 82

BD = Bulk Density / IWC = Initial Water Content (1 min of immersion) / FWC = Final Water Content (48 h of immersion) / K_1 = Diffusion rate of water.
$^{(*)}$ Without and with compaction.

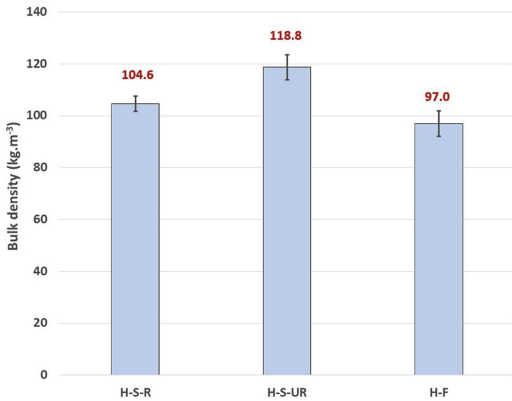

Fig. 6. Bulk density of the dried hemp samples.

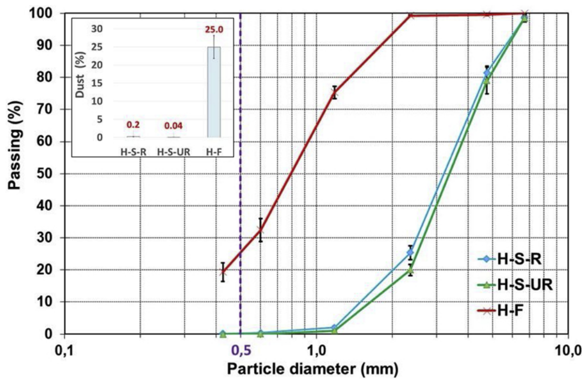

Fig. 7. Particle size distribution and dust ratio of the dried hemp samples.

5.2. Sound absorption coefficient

Fig. 8 compares the sound absorption of a small chop hemp hurd retted sample (H-S-R) with 2 different bulk densities. Performance is similar to that previously reported for French hemp with approximatively the same size and the same bulk density [9]. The reproducibility of the results is good and the procedure to fill the holder has a low influence as observed in Ref [11]. The same repeatability was obtained for the three different kinds of hemp samples. The average results of the

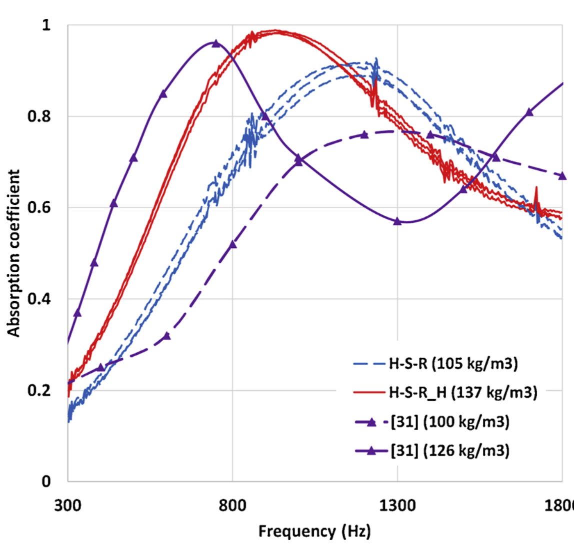

Fig. 8. Sound absorption coefficient for the retted shiv with 3 different samples (2 bulk densities) and results in Ref. [31] (H index = compaction to obtain an 30 % increasing of the bulk density).

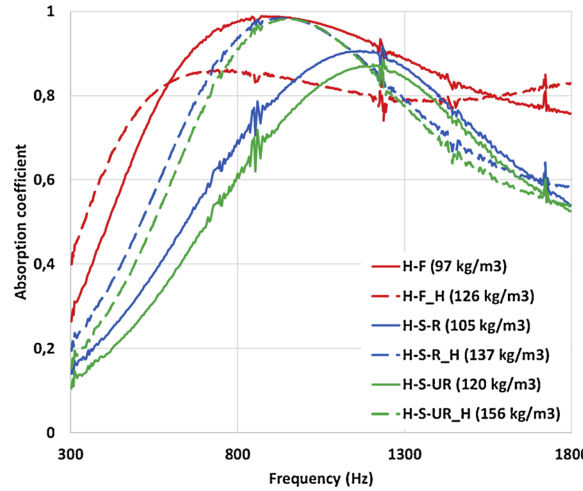

Fig. 9. Sound absorption coefficient for 3 different hemp and 2 bulk densities (H index = compaction to obtain an 30 % increase of the bulk density).

tested hemp samples with the bulk densities are reported on Fig. 9. The sound absorption of the retted hurd (H-S-R) is slightly more efficient than the unretted hurd (H-S-UR) with 0.92 against 0.88 at 1200 Hz. This better behaviour could be explained by the lower bulk density and volume solid fraction of the retted shiv in comparison to the unretted one. Without compaction, the fine hemp (H-F) is the most efficient acoustic barrier with a sound absorption of about 1 for a frequency of around 900 Hz. If only fines particles are used, as depicted in the particle size distribution analyse, the complexity of sound path increases the energy loss. An increase of about 30 % in the bulk density leads to a change in pore size distribution and a shift of the absorption curve toward the lower frequency with 950 Hz for H-S-R and H-S-UR samples and 700 Hz for H-F sample. For the hurd samples (H-S-R and H-S-UR), an enhancement of the amplitude is also observed because of the modification of the pore size distribution. In fact, a lower intraparticle porosity increases the tortuosity, which lead to an entrapment of sound. On the contrary, for the fine samples (H-F), the compaction causes a reduction of the amplitude. In this case, the hemp is packed too densely resulting in very low porosity, which restricts the sound wave to penetrate the absorber as previously reported in Ref [11,45]. Following the particle size distribution of each hemp samples, an optimum degree of compaction has to be determined.

5.3. Thermal experiments

The thermal conductivity of the three samples with the two levels of compaction are depicted on Fig. 10. The average value for the hurd samples (H-S-R and H-S-UR), without compaction, is 88 $mW.m^{-1}.\ K^{-1}$. This result is very close to previous studies [39], which have also conducted tests with a hot wire equipment, with a thermal conductivity around 73.5 $mW.m^{-1}.\ K^{-1}$. Moreover, for both compacted and no-compacted samples, the retted hurd (H-S-R) is more efficient for thermal insulation than the unretted hurd (H-S-UR). The same reasons as for the sound absorption coefficient, a lower density and a lower volume solid fraction, explain the lower thermal conductivity of the retted hurd. Indeed, Fig. 11 shows a linear increase of the thermal conductivity as a function of the bulk density as show in literature [20]. The fine hemp sample (H-F) has the lower conductivity with 64 $mW.m^{-1}.\ K^{-1}$, without compaction, and 82 $mW.m^{-1}.\ K^{-1}$, with compaction. Its lowest bulk density is an explanation for its thermal performance. Moreover, its finer particle size distribution, with a lot of dust, must have a significant effect, which yet to be investigated. Its use into a render mix, is a potential way to improve the thermal efficiency of the existing buildings.

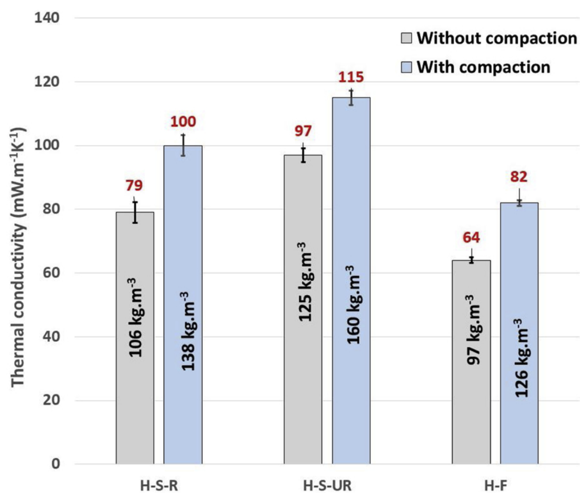

Fig. 10. Thermal conductivity for 3 different dried hemp and 2 bulk densities (compaction to obtain 30 % increase of the bulk density - Bulk densities are given in the columns of the histogram).

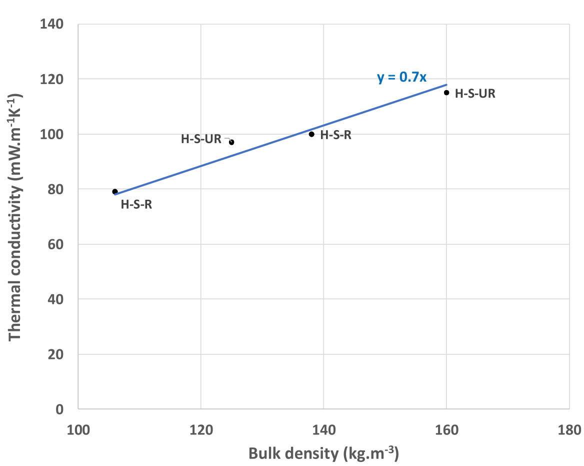

Fig. 11. Thermal conductivity as a function of bulk density for retted (H-S-R) and unretted (H-S-UR) hemp in a dry state.

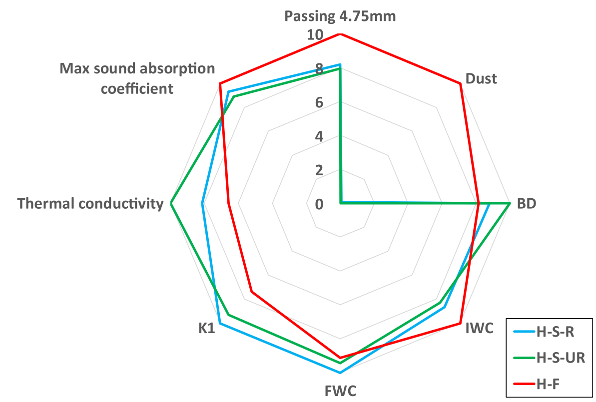

Fig. 12. Comparison of some characteristic of the hemp tested (BD = Bulk Density, IWC = Initial Water Content after 1 min of immersion, FWC = Final Water Content after 48 h of immersion, K_1 = Diffusion rate of water) - For each characteristic, the highest value obtains 10 mark.

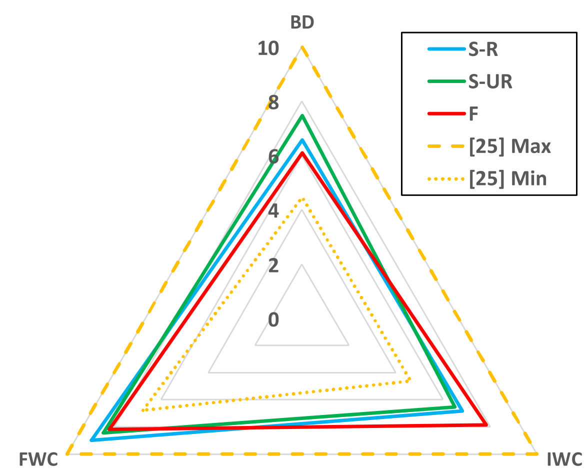

Fig. 13. Comparison of some characteristic of the tested hemp with the European results (BD = Bulk Density, IWC = Initial Water Content after 1 min of immersion, FWC = Final Water Content after 48 h of immersion).

5.4. *Multicriteria analysis and comparison with European results*

To compare all the characteristics of the different tested hemps, a multicriteria analysis was performed. A unidimensional scale ranging between 0–10 was used, the highest value of each characteristic obtaining 10 marks. Fig. 12 provides an overall view of the main results obtained. Fig. 13 compares the bulk density (BD), the final water content (FWC) and the initial water content (IWC) with European results [25]. One of the main impact of the retting process is on the bulk density, and therefore the volume solid fraction, which affect the thermal and acoustic properties. A 12 % decrease of the bulk density causes a 5 % increase of the sound absorption coefficient (without compaction) and a 19 % decrease of the thermal conductivity. The other characteristics are observed to be very close between the unretted and retted hemp. With a view to enhance insulation performance of hempcrete, it seems better to use a dew retted hemp which has a lower bulk density and better thermal and acoustic properties. The use of the fine particles as aggregate in a render should enhance the thermal and acoustic properties of the render. In order to find the most efficient mix, the key aspects to consider are the workability of the mix and its application. In spite of the different environmental conditions, the properties of Australian shiv is found to be close to that of European ones, with a bulk density and a water absorption within the same range as that European shivs.

6. Conclusions

The main influence of the retting process on shiv is a decrease of the bulk density which is the result of hemp degradation, enhancing its thermal and acoustic performance. The retting process have a positive effect on the shiv's insulation properties. The use of by-product fine particles, from the hemp industry, as an aggregate into a render could be an efficient way to improve the acoustic and thermal properties. Moreover, porous renders enable to maintain the breathability of biocomposite concrete and preserve the durability of the material. In comparison with previous studies using European shiv in hempcrete, the tested hemp farmed in Australia, has similar acoustic, thermal and mechanical properties.

In order to better understand the influence of the retting process on the shiv performance, chemical and microstructure analysis have to be performed. In addition, the influence of the retting process on the durability of the hempcrete will have to be assessed. Research on the development of an ecofriendly binder, to mix with Australian hemp, are ongoing in order to achieve a sustainable material with high insulation properties.

Data availability

The raw data required to reproduce these findings are available to download from http://geomas.insa-lyon.fr. The processed data required to reproduce these findings are available to http://geomas.insa-lyon.fr/.

Declaration of Competing Interest

None.

Acknowledgments

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.mtcomm.2020.100986.

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