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Highlights

- Flax shives waste and lime binder were used to make a new building material with a low environmental footprint.
- The effect of particle size and flax to binder ratio on flax concrete behaviour was investigated.
- The hygrothermal properties of flax concrete were highlighted.
- Flax concrete is an excellent moisture regulator with a minimum and maximum MBV index of 2.03 and 2.82, respectively.
- Flax concrete is a pertinent solution to improve the energy efficiency of buildings.

Abstract

This paper presents an experimental investigation of the hygrothermal and mechanical properties of green concrete containing different content and size of flax shives. This allows it to respond to different applications in the building domain. Results of microscopic observations by using scanning electron microscopy show that the flax shives have a very complex and porous microstructure. The latter allowed for good hydric and thermal behaviour with a high moisture buffer capacity of which the minimum and maximum were 2.03 and 2.82, respectively. This allows it to be classified as an excellent moisture regulator. Flax concrete with a mass composition of 14.5% of flax shives in bulk, 35% of binder (tradical PF70) and a water-to-binder ratio of 1.45 gave a bio-based material with an average compressive strength of 0.8 MPa; it is, therefore, used as an insulation and filling material in buildings.

Keywords: flax concrete; microstructure; hygrothermal properties; moisture buffer capacities; compressive strength.

1. Introduction

The building sector is the largest consumer of energy in the world and is responsible for a large amount of greenhouse gas emissions [1–3]. In order to limit the impacts of climate change, several United Nations organisations [4] (Conference Of the Parties (COP), National Low Carbon Strategy (NLCS), Intergovernmental Panel on Climate Change (IPCC), etc.) have put strategies and action plans in place. In this context, the repair and construction of new high-performance buildings is now crucial because it is an important economic issue and needs improved energy efficiency envelopes, while considering the carbon footprint. In fact, buildings must consume less energy and their overall environmental impact must also be reduced but without ignoring the growing demands for indoor air quality and occupant comfort. The choice of building materials now seems to be a key factor in the success of a project (in terms of achieving high environmental qualities (HEQ) [5,6]) in order to meet the requirements of sustainable development. With this perspective, the use of bio-based materials constitutes an interesting solution because, on the one hand, they are known for their insulation properties [7–10] and, on the other hand, they provide opportunities for recycling natural waste and environmental protection [11–13]. In fact, materials with a low environmental footprint have a negative carbon balance [14] and are a good solution for reducing energy use and environmental impacts. However, the behaviour of these bio-based materials remains poorly reported in the literature, which has made their use by industry professionals limited. That being said, several research studies have been performed on hemp shives [9,15–21] that can be used for bio-based construction materials, such as hemp concrete [16,22–24]. This insulation material is composed of hemp shives incorporated in a binder (lime) and water [25]. The life cycle analysis of hemp concrete revealed a negative carbon balance and low, grey energy. In fact, one square metre of this 25 cm thick material requires up to 370-394 MJ of energy for production and can store up to 35 kg of CO_2 over 100 years, unlike an equivalent cellular concrete wall that requires up to 560 MJ of energy for production and ultimately releases 52.3 kg of CO_2 [26,27]. This means that the amount of CO_2 released during the production of hemp concrete is compensated by the amount absorbed during its life cycle, which better protects the environment.

Furthermore, some researchers [9,16,25,28] showed that hemp shive panels and hemp concrete are a good insulation materials with promising physical and hygrothermal properties. Its porous structure and low density reduces thermal conductivity to 0.1 W/(mK) compared to the conventional materials such as the Portland cement concrete, block and brick [25,29,30]. Indeed, thermal conductivity is strongly related to the composition of the hemp concrete. Since the hydraulic lime binder is more conductive than hemp shives, the global thermal conductivity of the material increases with the binder content. Moreover, hemp concrete is a breathing material with excellent moisture buffering capacity and high water vapour permeability [25,31]. These properties make this material a natural moisture regulator and allow it to limit daily variations of the relative humidity in order to ensure good indoor air quality [32,33].

In addition to hemp concrete, several other vegetative aggregates were used to make sustainable building materials in order to recycle natural wastes, protect the environment and reduce the energy consumption of buildings. Among these vegetative particles, flax shives [13,34,35] present a low thermal conductivity. Indeed, flax concrete, composed of flax shives, binder (mainly lime) and water, has a high water absorption capacity of approximately two to three times its weight within 48 hours because its pores are organised in parallel capillaries [36,37] and its high cellulose content of about 48 % [36,38].

Recent contributions to the literature have presented research on flax concrete, which has begun to be developed more and more because of its energy and environmental performance. Among these contributions, we quote the Grow2Build project, based at Brunel University [39]. It provided a database of building materials based on hemp and flax particles. The aim was to promote the use of hemp and flax as raw materials for construction products in the North West European region. Furthermore, Khazma *et al.* [40] studied the effects on the properties of vegetative flax particles by treating them, using a mixture of pectin/polyethyleneimine to coat the flax shives in a cementitious material. They showed a reduction in dimensional variations, water absorption times and setting times and an increase in the enthalpy of cement hydration. An increase in the mechanical strength was also noted, as well as a slight increase in thermal conductivity and bulk density.

In another study, Khazma *et al.* [41] investigated the effects of the treatment of flax shives on their physico-chemical properties, in addition to the physico-mechanical properties of flax shives-based cementitious composites. They showed that treating flax shives with raw and emulsified linseed oil improved the vegetal/matrix compatibility. Moreover, the hydric and mechanical performance of the composite was improved. Page *et al.* [42] carried out an experimental study on the influence of different surface treatments of flax fibres on the properties of fresh and cured mortars. They showed that the coating of these fibres reduces the water absorption capacity and improves the workability of the mortar. However, a large specific surface area of the flax fibres was responsible for workability disturbances and none of the treatments studied actually improved the mechanical properties of the cured composite. Rahim *et al.* [37] compared the hydric properties of flax and hemp concretes. They showed that flax concrete presents a high hygrometric performance with an excellent humidity buffer capacity, according to the Nordtest project [43]. Finally, Garikapati *et al.* [13] studied the mechanical behaviour of flax-lime concrete reinforced with jute fabric. They showed that the position and number of layers of the jute fabric (reinforcement) increased the bending and energy absorption capacity of this material. The authors suggested the use of this system in buildings as a filling and insulation material.

To our knowledge, apart from the few studies presented above, flax concrete is not well reported on in the literature, which has reduced its current use in construction. This paper proposes to address this problem and overcome the limitations of use of flax concrete by enriching the literature database. The aim is to better understand the behaviour of flax concrete in order to efficiently master its use in construction and, thus, make the transition to the green sector with very high potential for the entire building sector. Experimental investigations of the hygrothermal and mechanical characterisation of several formulations of flax concrete were proposed in this study. Nine formulations of flax concrete have been studied, in terms of content and particle size of the plant matter. The investigation covers the porosity, density, thermal conductivity, the moisture buffer value (MBV), sorption isotherms, moisture storage capacity and compressive strength.

2. Material and methods

This study was performed on an innovative material based on vegetative particles, namely flax concrete. An important experimental characterisation campaign was carried out on this material, considering the effect of the vegetative particle size and formulation on the physical, hygrothermal and mechanical properties of the material. Flax concrete was obtained by mixing vegetative aggregates (flax shives), binder and water. The flax shives were provided by the agricultural cooperative company C.A.L.I.R.A (Abbeville-France) and had an apparent density ranging from 100 to 140 kg/m^3 and dimensions of 1 to 35 mm. The binder used was the Tradical PF70 lime product, provided by the manufacturer Ecohabitat (L'Isle-d'Espagnac-France). The binder comprised 75% air lime, 15% hydraulic binder and 10% pozzolanic binder.

For this study, nine formulations of flax concrete with different contents and vegetative particle sizes were tested. Firstly, we fixed three different sizes of flax shives: medium, large and bulk size (Figure 1). Secondly, for each size, three content percentages of the flax shives were proposed: 11.5%, 14.5% and 17.5%. The aim was to represent the different applications of flax concrete, which depends on the formulation of the material. These content percentages were based on the standard formulation of hemp concrete [25]. In addition, three corresponding water/binder ratios (W/B) were used: 0.31, 0.42 and 0.54. The formulations are summarised in Table 1.

Figure 1. Photo of the flax shives used: (a) bulk size, (b) medium size, and (c) large size.

Table 1. Different formulations of studied flax concrete

Flax shives size	Formulation abbreviations	Percentage Mass Flax shive (%)	Water/binder (W/B)	Flax/binder (F/B)
Bulk Size (BS)	**F1-1**	11.50	1.35	0.31
	F1-2	14.5	1.45	0.42
	F1-3	17.50	1.55	0.54
Medium Size (MS)	**F2-1**	11.50	1.35	0.31
	F2-2	14.5	1.45	0.42
	F2-3	17.50	1.55	0.54
Large Size (LS)	**F3-1**	11.50	1.35	0.31
	F3-2	14.5	1.45	0.42
	F3-3	17.50	1.55	0.54

For the formulation abbreviations in this article, Fi-j means the following:

$$\begin{cases} \text{F: studied formulation.} \\ \text{i} = (1,2,3) \text{ defines the size of the flax shives (bulk, medium and large, respectively).} \\ \text{j} = (1,2,3) \text{ defines the mass content of flax shives (11,5\%,14.5\% and 17.5\%, respectively).} \end{cases}$$

In order to better show the variation in particles size of the vegetative aggregates, a granulometric analysis of the flax shives was performed by image processing, according to the RILEM recommendations [44]. Vegetative flax particles with different sizes (BS, MS, and LS) were deposited on a black sheet. The use of a black background allowed us to facilitate the segmentation operation (see Figure 2). The results of granulometric analysis by image processing (performed using ImageJ software) are presented in Figure 3.

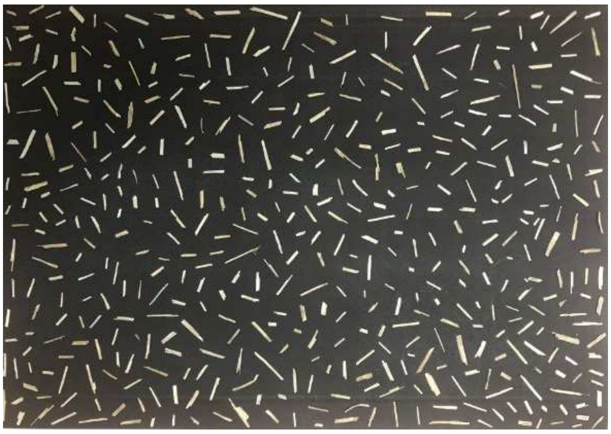

Figure 2. Example of the arrangement of flax shives on a sheet of A4 paper.

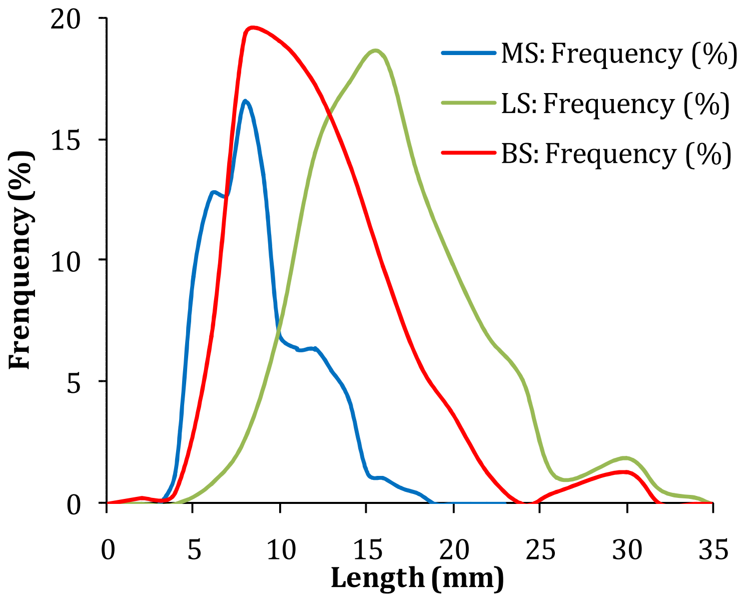

Figure 3. Characterisation of different lengths of flax shives by image processing: (MS) medium size, (LS) large size and (BS) bulk size.

The flax concrete specimens (of dimensions 15×15×5 cm, 10×10×40 cm and Φ11×22 cm) were de-moulded within four days of manufacture. Then, they were stored in a climatic chamber, with regulated temperature and relative humidity (T = 20°C and HR = 50%). The material characterisation was only started after their mass stabilisation. The age of all the samples used, at the beginning of characterization, was 4 months. In this study, the characterisation was focused on the functional properties of flax concrete, namely: density, porosity, thermal conductivity, sorption isotherms, moisture storage capacity, MBV and compressive strength.

2.1. Porosity test

The porosity test was carried out using water and was performed according to the French association AFPC - AFREM [45]. This method is based on vacuum saturation, using a saturation bench, and then carrying out three separate weighings. The first is the hydrostatic weighing of a saturated sample immersed in water (M_{water}). The sample is then weighed in air after extracting it from the water (M_{air}). Finally, the third weighing corresponds to the dried sample (M_{dry}). The porosity was calculated using Eq. (1):

$$\varepsilon_p = \frac{M_{air} - M_{dry}}{M_{air} - M_{water}} \times 100\ (\%) \qquad (1)$$

2.2. Environmental Scanning Electron Microscopy (E-SEM)

In order to better investigate the microstructure of the flax concrete, it was analysed by scanning electron microscopy in environmental mode. In this mode, no preparation of the sample during the analysis is required. It avoids possible morphological disturbance and preserves the microstructure of the sample tested. In fact, this SEM (with controlled pressure) allows the observation of wet samples without prior metallisation, even in the presence of liquid. An accelerated voltage of 20 kV and different magnification levels were chosen to observe the microstructure of the studied materials: magnification ×78 and ×800 for the flax shives and ×57 and ×200 for the flax concrete samples.

2.3. Compressive strength

The compressive strength test was performed as per European standard EN 826 [46] and ASTM C109 [47]. Three cubic 5 cm samples were tested using a hydraulic press (Zwick Roell®) with a displacement rate of 5 mm/min and a maximum load of 100 kN.

2.4. Thermal conductivity

Thermal conductivity is one of the most influential properties on the thermal behaviour of buildings. It represents the ease of heat propagation in a material for a given temperature gradient. This property was measured for a fixed temperature of 23°C using the Lambda-meter Ep500e device, based on the guarded hot plate and according to the standards presented in [48] and [49]. The samples were placed between two plates of different temperatures. In addition, a guard ring was placed around the sample in order to ensure unidirectional heat flow through the thickness of the sample. Finally, the thermal conductivity was deduced from the electrical power (*U.I*) and the temperature gradient between the two plates (ΔT) as shown in Eq. (2). The sample size was 15×15×5 cm.

$$\lambda = \frac{U.I.e}{\Delta T.A}\ [w/(m.K)] \qquad (2)$$

where e is the thickness of the sample and A is the exchange surface.

2.5. Sorption isotherms

Water vapour sorption isotherms represent the evolution of the water content of a material in equilibrium with the relative humidity of the air for a given temperature. These sorption isotherms were measured using the ProUmid® SPS device, based on the gravimetric method principles. Indeed, the tested samples were placed in the climatic chamber of the device and exposed to different levels of relative humidity at a temperature of 23°C. The adsorption/desorption isotherms were obtained from the mass variation (gain/loss) of the samples at equilibrium, monitored by a precision scale (accurate to 10^{-4}g). The samples used had first been dried at 40°C under a vacuum until mass stabilisation.

2.6. Moisture Buffer Value (MBV)

The moisture buffering capacity characterises the material's ability to moderate changes in the relative humidity of the ambient air. This parameter was measured as per the Nordtest project. The principle of the MBV test protocol is to expose the samples to daily relative humidity cycles in order to be representative of the cycles encountered in buildings. The relative humidity used was 75% and 33%, with an exposure time of 8 hours in adsorption and 16 hours in desorption. In addition, the samples were previously conditioned at 23°C and 50% RH, up to the equilibrium. The measured samples were 10×10×5 cm. The Nordtest project classified materials according to their moisture buffering capacity, as shown in Figure 4.

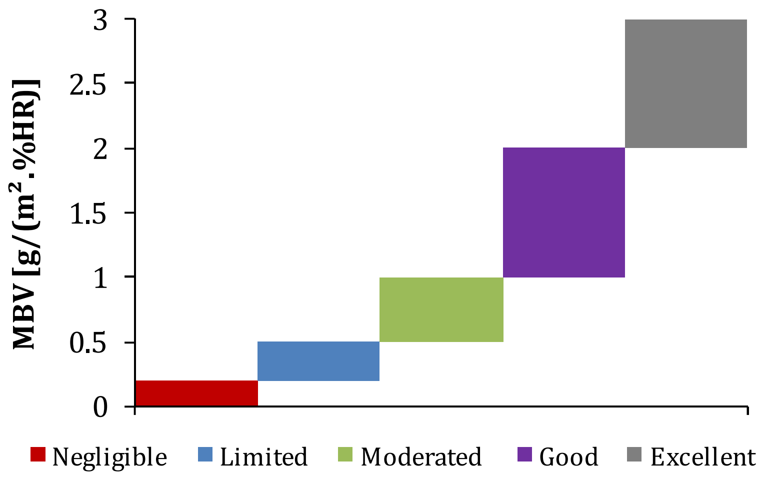

Figure 4. Nordtest project classification of materials versus Moisture Buffer Value [43].

Mass tracking of the samples allows us to be able to determine the Moisture Buffer Value of the flax concrete according to Eq. (3):

$$MBV = \frac{\Delta m}{A(HR_{max} - HR_{min})} \quad (3)$$

where MBV [g/(%HR.m^2)] is the Moisture Buffer Value, Δm [g] is the mass variation during the absorption/desorption phase, A [m²] is the exposed sample surface area and $\mathrm{HR_{max}}$, $\mathrm{HR_{min}}$[%] is the maximum and minimum relative humidity applied during the humidification and drying cycle, respectively.

3. Results and discussion

3.1. Scanning electron microscopy analyses

The vegetal particles (flax shives) were observed by the Scanning Electron Microscope in Environmental Mode. This allows the preservation of the microstructure of the tested sample by keeping its hydric state with the controlled pressure. Figure 5 illustrates the SEM images of the cross and longitudinal sections of the flax shives at two different observation scales. Firstly, it can be noted that despite the thinness of this flax particle (average thickness about 300 µm), its cross-section shows a porous and very complex structure with pores of different sizes and geometries. According to the literature, the walls forming these porous cells consist mainly of cellulose, hemicellulose, lignin and pectin [50,51]. From Figure 5, we also notice that the pores of the flax shives are organised in capillaries parallel to the growth direction of the plant. In addition, these capillaries are connected to each other through small cavities (see Figure 5 (d)). One the one hand, this porous and complex structure allows dampening of the transmission of heat in the flax shives, which consequently gives it a low thermal conductivity and, on the other hand, it allows an increase in water absorption and hydric transfer capacities. The incorporation of these plant particles into a lime-binder can, therefore, improve the hygrothermal properties of the material.

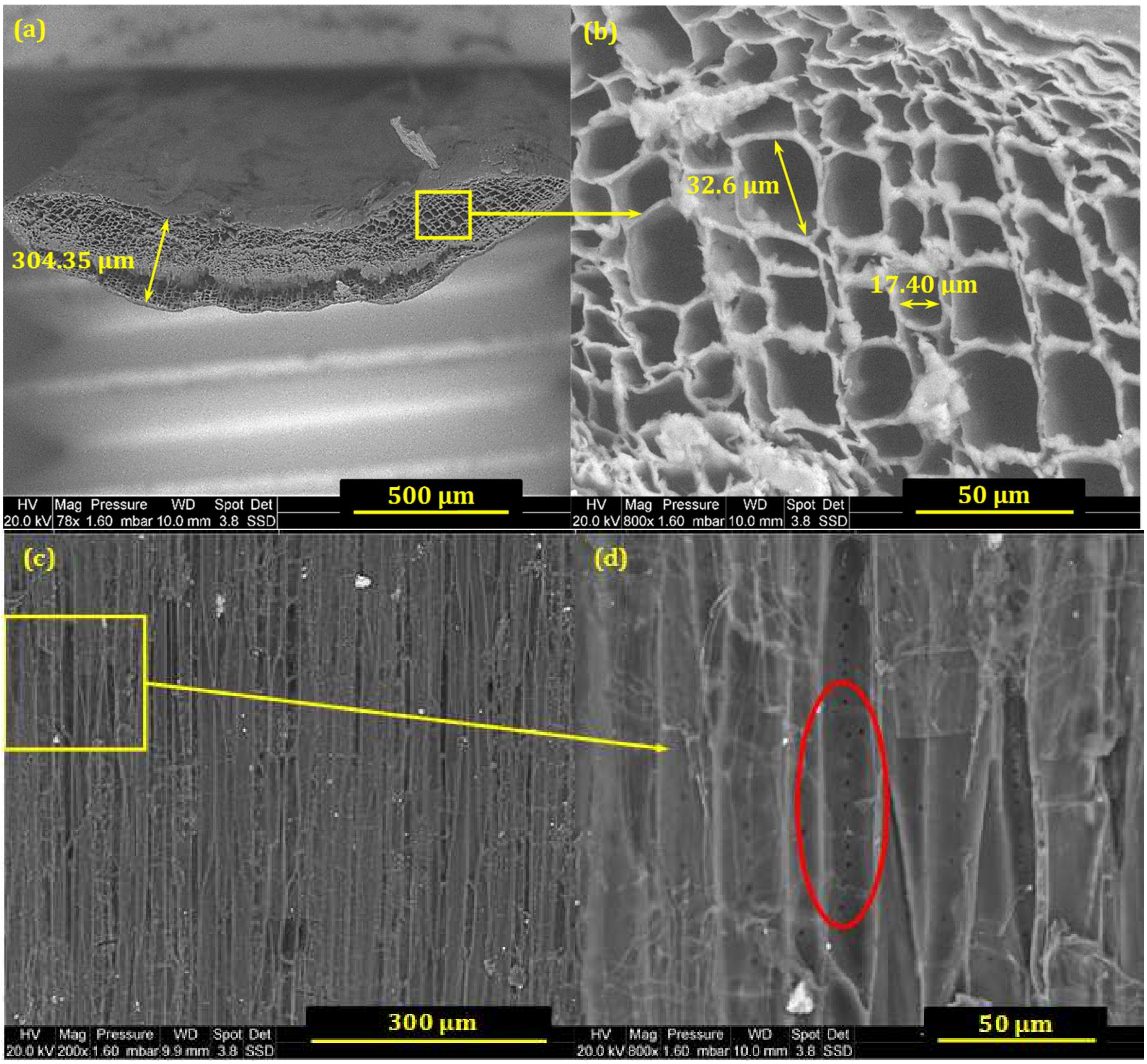

Figure 5. (a) and (b) Cross-section of the flax shives and, (c) and (d) Longitudinal section observed at SEM at different magnification.

Moreover, Figure 6 illustrates the SEM observations of flax concrete. This overview shows that the flax shives are well embedded in the binder (Tradical PF70). However, some cracks can be observed in the particle/binder connection interface. This can be explained, on the one hand, by the contamination of vegetative particles from the binder [52–54]. Researchers [52,53] showed that the surface of the vegetative particles was covered with CaO-rich phases. Particles of $Ca(OH)_2$ in flat shape and CaO-rich gel were noticed. Indeed, theses vegetative particles such as hemp and flax particles have the ability to trap calcium in their pectin structure and then to form CaO-rich gel on the surface of the particles. On the other hand, the observed cracks can be attributed to the hydrophilic nature of the vegetative particles [17,19]. The latter presents a high adsorption capacity which reaches up to three times their weight in 48 hours [36,37]. This hydrophilicity can draw water out of the binder existing for its hydration. This could also cause the swelling of the flax shives in case of humidification or their shrinkage in case of drying. These two phenomena can therefore be at the origin of the micro-cracks observed at the binder/flax shives interfaces. This may have a negative effect on the mechanical behaviour of this material.

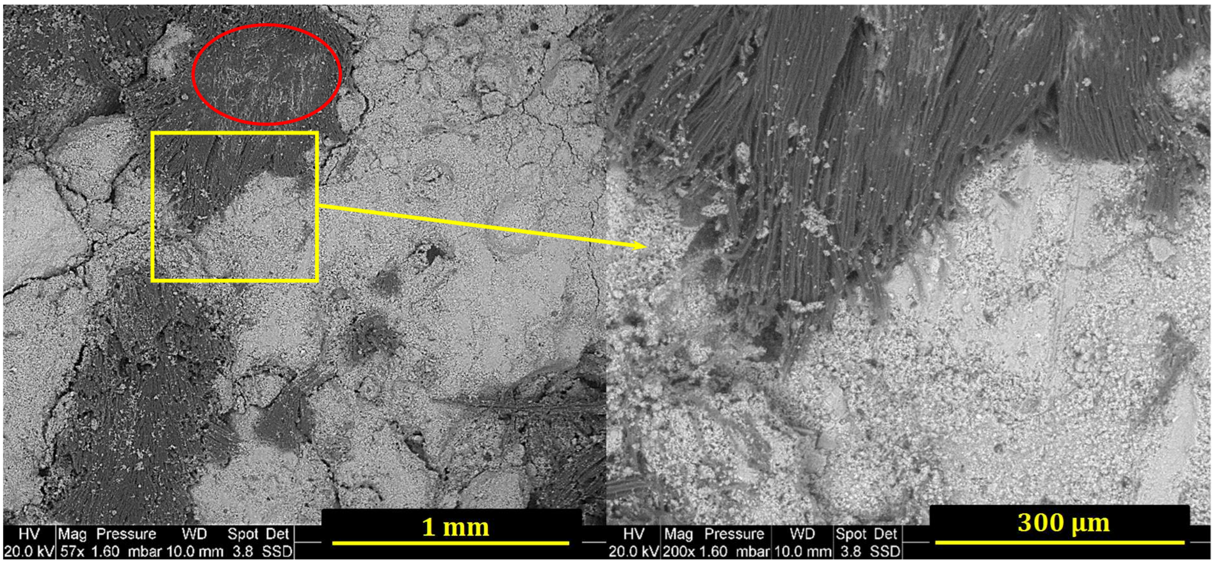

Figure 6. SEM images of flax concrete: adhesion binder /flax shives.

3.2. Density and porosity

For each formulation of flax concrete, three density measurements were performed after drying the samples in a kiln for 7 days at 50°C. The average densities and their standard deviations are shown in Figure 7. Firstly, the density of the flax concrete with the standard formulation (W/B ratio of 0.42 and F/B of 1.45) was about 550 kg/m^3. Furthermore, the size of the flax shives did not affect the density of the flax concrete. The latter has the same order of magnitude for each size of flax shives. On the other hand, the density of flax concrete was significantly affected by the quantity of the flax shives used, decreasing with the flax shives content. For example, in the case of bulk size, the density goes from

638 kg/m^3 to 468 kg/m^3 for F1-1 and F1-3 formulations, respectively. This is due to the density of plant particles (about 110 kg/m^3), which is very low compared to that of the binder, estimated at an average of 1200 kg/m^3. This property made the flax concrete a light and porous material for use in construction.

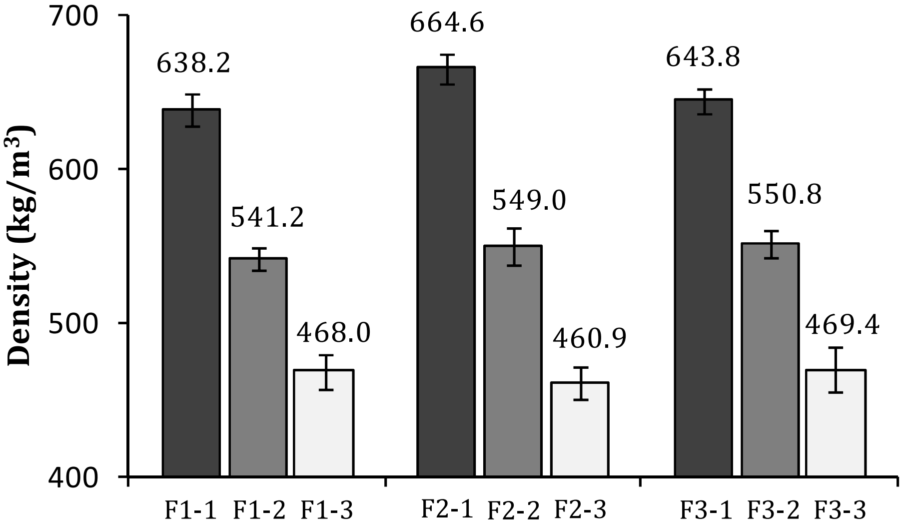

Figure 7. Density of the different formulations of flax concrete.

In addition, the porosity of flax concretes was measured. The average porosity (and its standard deviation from three measurements) are presented in Figure 8. The average porosity of flax concretes used ranges between 72% and 76%. These values were in agreement with the hemp concrete porosity found in the literature [55]. In general, we noted that the size of the flax shives did not affect the porosity of flax concrete. However, a slight porosity increase of flax concretes versus the flax shives content was observed. Indeed, this increase is clearly shown between the flax concretes containing 11.5% of flax shives and ones containing 17.5% of flax shives. This is due to the high porosity of flax particles (as shown in the SEM images in Figure 5) and the increase of the intergranular voids. The porosity results are in agreement with the densities shown above.

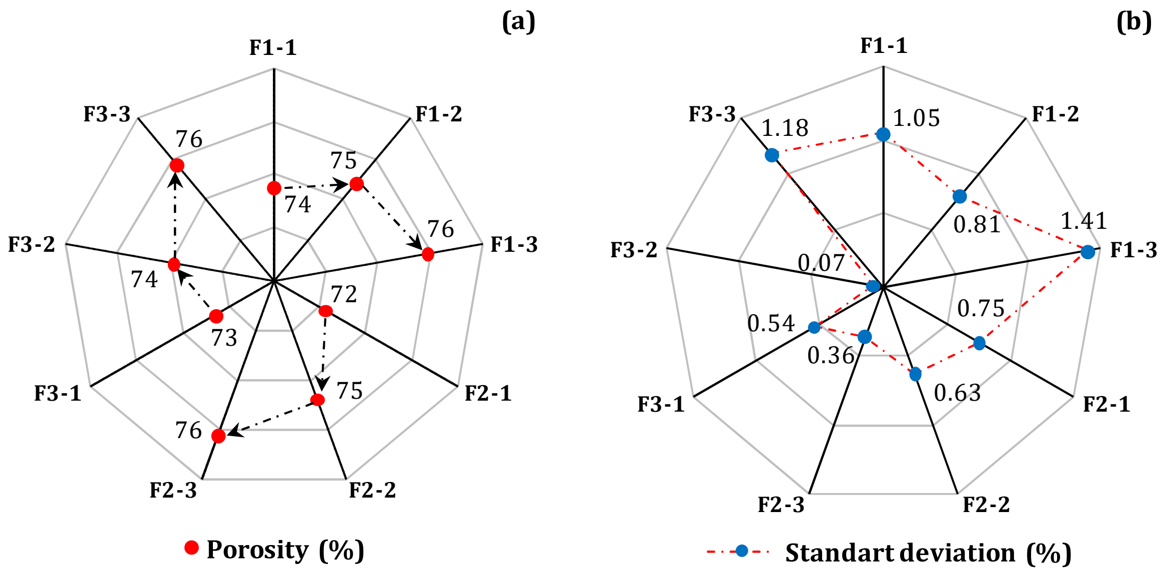

Figure 8. (a) porosity of different formulations of flax concrete and, (b) its standard deviations.

3.3. Hygrothermal properties

First of all, we are interested in the insulation properties of flax concrete. Thermal conductivity is an important property which characterises the thermal behaviour of the material. To ensure good repeatability of results, three measurements were carried out for each formulation. This property was measured at 23°C. The average thermal conductivities and their standard deviations are shown in Figure 9. The average thermal conductivity of 'standard' flax concrete was approximately 100 mW/(m.K), which remains much lower than other construction materials, such as cementitious concrete, estimated at 1200 mW/(m.K) [29,30,56]. The actual value confirms the insulation property of flax concrete. Moreover, we noted that the thermal conductivity of flax concrete decreases with the amount of the flax shives used. Indeed, the thermal conductivities of F2-1 (11.5% flax shives), F2-2 (14.5% flax shives) and F2-3 (17.5% flax shives) were 127, 104 and 84 mW/(m.K), respectively. In fact, the binder is more conductive than flax shives and so the more the binder dosage increases, the more the insulation properties of the material decrease. This reduction can also be explained by the density and the porosity of the flax concrete, which increases with the quantity of flax shives (as shown in Figure 7 and Figure 8), because the thermal conductivity of the air is lower than that of the binder and flax. This causes dampening of the heat transmission, resulting in a decrease in the thermal conductivity of the material.

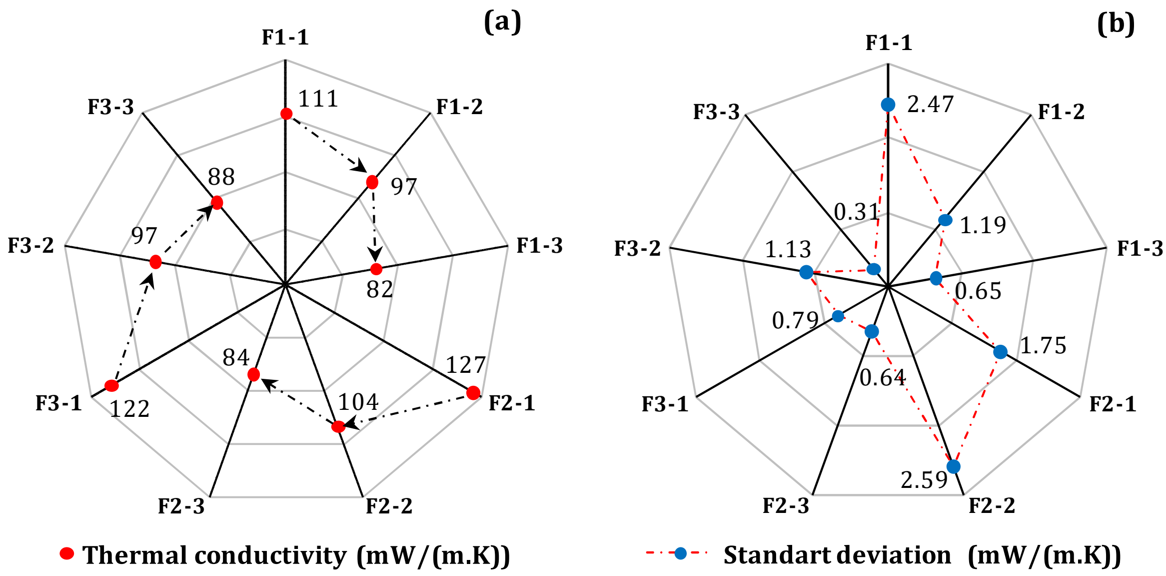

Figure 9. (a) Thermal conductivity of different formulations of flax concrete and (b) its standard deviations.

In addition, the size of the flax shives slightly affects the thermal conductivity of flax concrete. A good agreement between porosity and density values was observed except for F1-1, F2-1 and F3-1, where the thermal conductivity increases with the size of flax shives (about 14% for F2-1 and 10% for F3-1, compared to F1-1 (see Figure 9)). This could be due to the random distribution of the particles used for this formulation (bulk flax shives), which engenders a complex microstructure.

Indeed, literature studies have shown that thermal conductivity of the vegetative particles is greater in the longitudinal direction than in the transverse one [24,57–59]. This is due to the anisotropy of the vegetative particles and their porosity organised in the longitudinal direction (Figure 5). This geometric arrangement leads to slower heat transfer in the transverse directions due to the large pores which have a thermal conductivity much smaller than those of the cell walls of the particle solid phase. For example in the case of hemp shive : the thermal conductivities of solid and air phases are respectively of the order of $0.5755\ W/m.K$ and $0.025\ W/m.K$ [58]. Therefore, hemp shive presents thermal conductivities of $0.08\ W/m.K$ and $0.122\ W/m.K$ respectively in the transverse and longitudinal directions of the particle [57]. In other words, the global thermal conductivity of flax concrete depends on the orientation and arrangement of the vegetative particles in the matrix and their relative percentage to one another.

We are now interested in the hydric properties of flax concrete, especially the adsorption/desorption isotherms, moisture storage capacity and the moisture buffer value. Sorption isotherms were evaluated at 23°C on three samples of each formulation. Figure 10 shows the average sorption isotherms for the three measurements. In order to better present the effect of the quantity and size of flax shives on the sorption isotherm of flax concrete, the adsorption/desorption isotherm curves of the material as a function of the F/B ratio (and for a constant particle size) are presented in Figure 10a, Figure 10b and Figure 10c. Furthermore, an example of a comparison between formulations F1-3, F2-3 and F3-3 (with the same flax shives content of 17.5%) is presented in Figure 10d and highlights the effect of the flax shives size on the change in water content, as a function of relative humidity.

Figure 10a, Figure 10b and Figure 10c show that the flax shives content affects the maximum moisture content on the sorption isotherm. Moreover, for the same relative humidity, more the F/B ratio increases, the higher moisture content at equilibrium. This observation can be clearly seen at high humidity levels (RH > 90%). For example, at 94% relative humidity, a moisture content increase of 26% for F3-3 has been noted compared to F3-1. This is explained by the high absorption capacity of the vegetative flax particles, which can achieve three times its weight in 48 hours. That being said, the absorption capacity of the flax concrete strongly depends on the amount of flax shives present. Finally, the size of the flax shives does not seem to have a significant influence on sorption isotherms, as shown in Figure 10d.

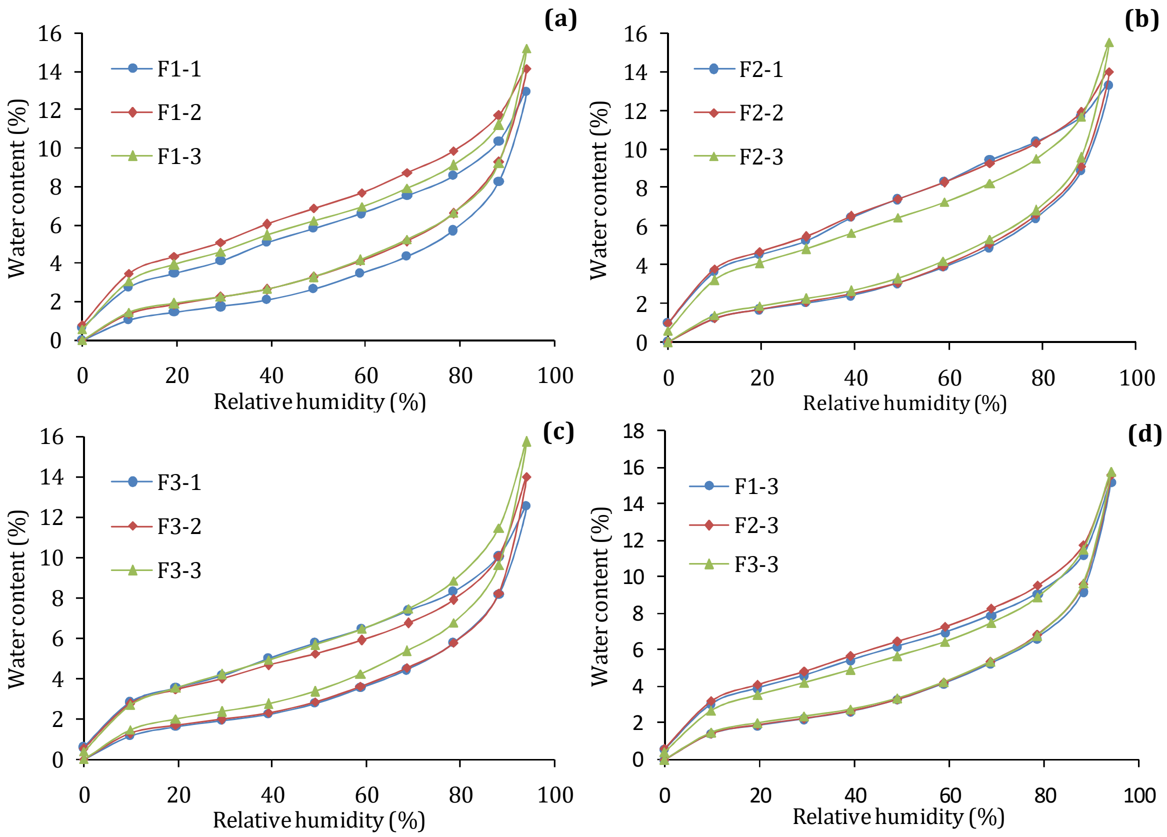

Figure 10. Sorption isotherms of flax concretes with different contents of (a) bulk flax shives, (b) flax shives of medium size and, (c) flax shives of large size. (d) Sorption isotherms of flax concrete with different shives sizes and content of 17.5%.

In addition, we observed that the area of the hysteresis loop during the desorption step varied randomly for the different flax concretes studied. This is due to the complexity of the material microstructures, which govern the hysteresis phenomenon. Indeed, the flax shives increase the inter-particle porosity of flax concrete and this changes the microstructure and pore size distribution of the material. So, in the case where the distribution of small pores dominates the microstructure of the material, water can get trapped inside because of the so-called "ink-bottle effect" and, consequently, the hysteresis loop will be wider. Indeed, during desorption, the emptying of large pores begins only after the emptying of small pores under relatively high capillary pressures. Therefore, if the capillary pressure necessary to evacuate the water is not reached, this water can remain trapped inside these pores and the emptying of the large pores is prevented, which explains the difference between the hysteresis curves observed.

According to the sorption isotherm curves, the moisture storage capacity values of the materials were deduced. The latter is an important input parameter for coupled heat, air and moisture models. It represents the ability of the material to adsorb and release moisture when environmental moisture conditions change [60] and is obtained from the slope of the sorption isotherms (see Eq. (4)).

$$C_m = \frac{du}{dHR} \quad (4)$$

where Cm is the moisture storage capacity [-], u is the water content of the material by weight [kg/kg] and RH is the relative humidity [%]. Figure 11a, Figure 11b and Figure 11c compare the influence of the flax shives content in flax concrete on its moisture storage capacity in the same manner as Figure 10. Based on these results, we noticed that when the relative humidity is below 80%, the flax shives content has practically no effect on the moisture storage capacity. However, at high relative humidity (RH > 80%), the moisture storage capacity increases with the flax shives content. Figure 11d shows the effect of the flax shives' size on the moisture storage capacity of flax concrete. No change between the different formulations was noticed. Furthermore, we can also observe that, independently of the size and flax shives content, the moisture storage capacity of flax concrete increases significantly above 80% relative humidity, hence the importance of considering this evolution in hygrothermal transfer modelling.

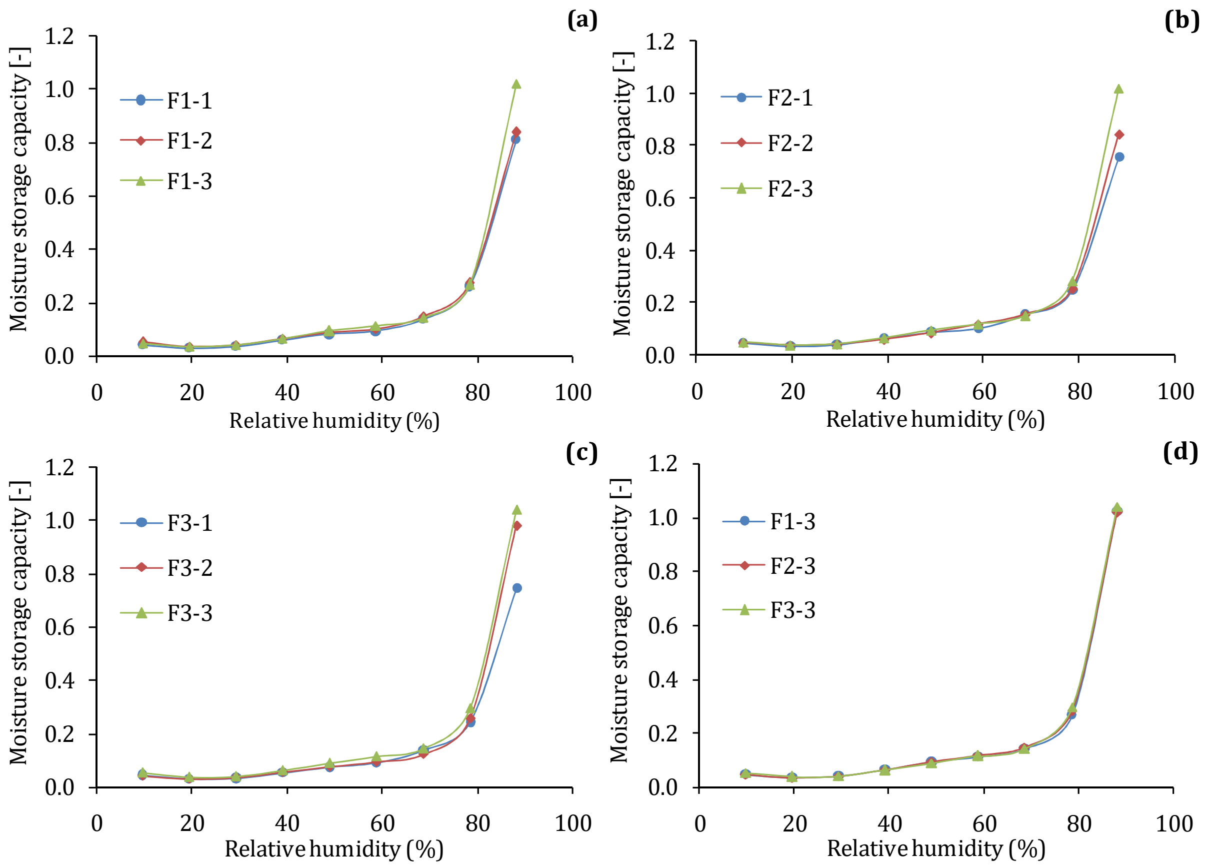

Figure 11. Moisture storage capacity of flax concretes with different contents of: (a) bulk flax shives, (b) flax shives of medium size and, (c) flax shives of large size. (d) Moisture storage capacity of flax concrete with different shives sizes and a content of 17.5%.

In addition, sorption isotherms can be simulated using the Guggenheim-Anderson-de Boer (GAB) model. For this purpose, we chose to simulate the isotherms of formulations F2-1, F2-2 and F3-2, using a variable flax shives size and a content of 14.5% (standard flax concrete). The aim of this was to enrich the database, in order to facilitate the reproduction of these isotherms for researchers who wish to model the hygrothermal behaviour of the flax concrete. This allows accurate reproduction of the experimental results. The expression for the GAB model is given in Eq. (5).

$$U = \frac{m.C.K.HR}{(1-K.HR)(1-K.HR+K.C.HR)} \tag{5}$$

where *U [kg/kg]* is the water content by weight at equilibrium, *φ [%]* is the relative humidity, *m* is the monolayer capacity, *C* is the kinetic constant relating to the sorption in the first layer, and *K* is the kinetic constant relating to multilayer sorption.

Table 2 presents the fitting parameters of the GAB model using experimental data for the three chosen formulations.

Table 2. GAB model adjustment parameters for the three modelled formulations.

Formulations	Model	m	C	K	R^2
F1-2		0.01826	24.19	0.9243	0.9963
F2-2	GAB	0.01798	18.07	0.9258	0.9968
F3-2		0.01496	52.88	0.9442	0.9951

It should be noted that this model precisely reproduces the sorption isotherms studied (see Figure 12). The minimum correlation coefficient between the experimental data and the adjustment curves is 0.995.

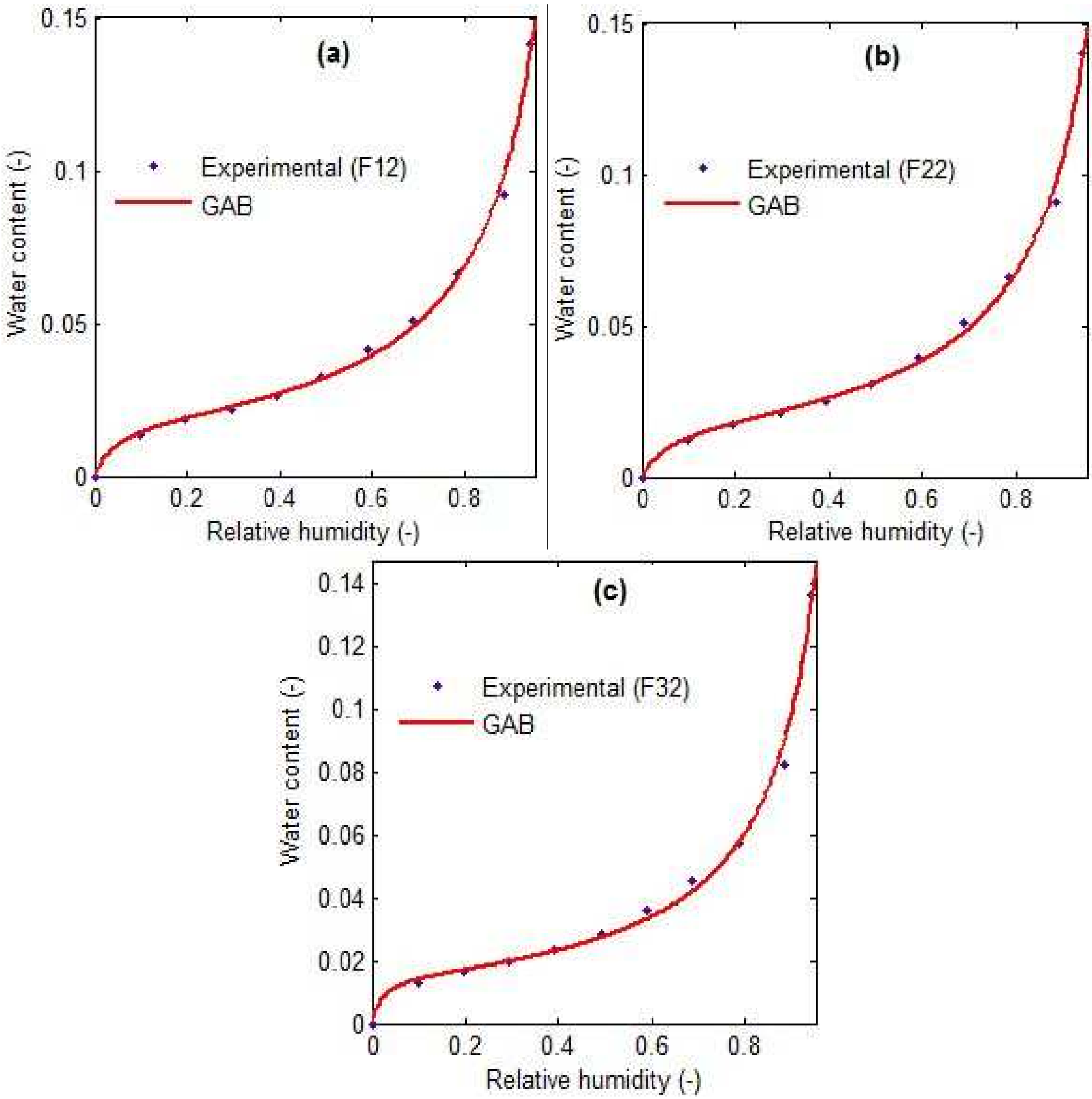

Figure 12. Sorption isotherm of flax concrete obtained by GAB model, at (a) F12, (b) F22 and (c) F32.

It is known that the bio-based materials such as hemp concrete efficiently regulate the ambient humidity in the building envelope. For this purpose, the moisture buffer capacity of flax concretes used was measured as per the Nordtest protocol. For each formulation, three measurements were performed. The average MBV values and their standard deviations are presented in Figure 13.

We note that the MBV values of the flax concretes used were greater than 2, which is in accordance with the literature [37]. Therefore, flax concrete can be classified as an excellent moisture regulator, according to the classification proposed by the Nordtest project (Figure 4). On the one hand, we note that the moisture buffering capacity of flax concretes strongly depends on the content of vegetative particles. This is due to the high moisture regulation capacity of the flax particles by adsorption and restitution of humidity. Therefore, the increase in the F/B ratio leads to a higher MBV value. On the other hand, we note that MBV index depends on the size of the flax shives. Concrete formulated with "large" flax shives had a slightly higher moisture buffer value than that of concrete with “medium” flax shives. For example, the MBV indexes for F3-1, F3-2 and F3-3 (with large flax shives) were 2.20, 2.52, and 2.81, respectively, while those of F2-1, F2-2 and F2-3 (with medium flax shives) were 2.03, 2.36 and 2.76, respectively. Large flax shives increase the moisture buffering capacity of flax concrete.

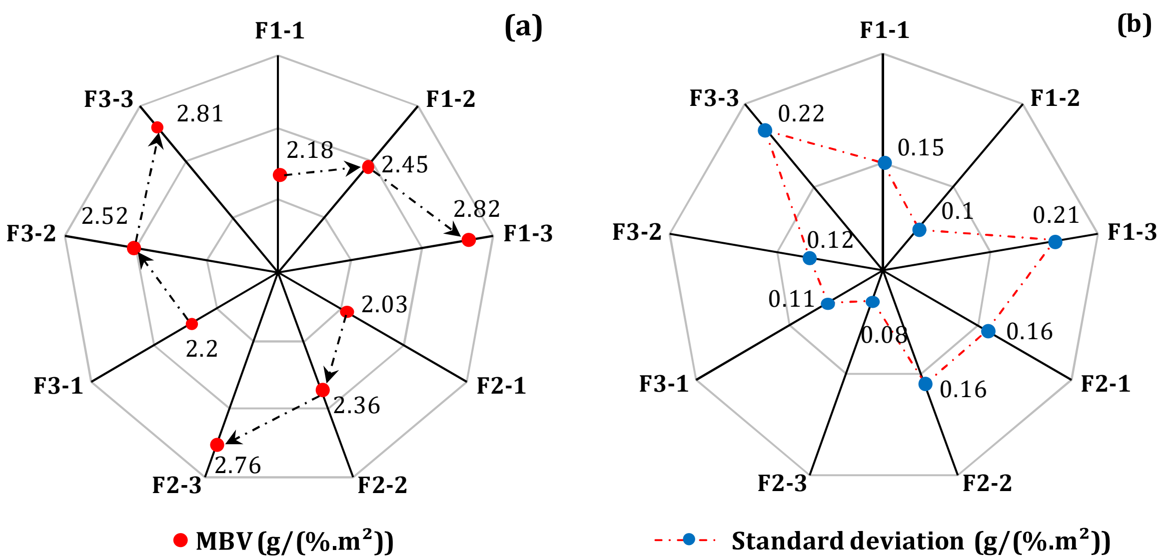

Figure 13. (a) Moisture buffer value (MBV) of flax concrete, (b) its standard deviations

3.4. Mechanical properties

Flax concrete is designed to be an insulator; it is used as a filling material in the building. However, a minimum compressive strength is required for insulating material, in order to support at least its own weight during installation. For this purpose, the compressive strength of the flax concretes used was measured on 3 samples. Average compressive strength and its standard deviation are shown in

Figure 14. The compressive strength of the flax concretes used ranged between 0.6 and 1.2 MPa; this is sufficient for use as insulating material in construction. The compressive strength of flax concrete is closely related to the quantity of the flax shives. The more flax shives content increases, the lower the compressive strength. For example, the compressive strengths of F2-1 (containing 11.5% flax shives), F2-2 (containing 14.5% flax shives) and F2-3 (containing 17.5% flax shives) were 0.9, 0.7 and 0.6 MPa, respectively. This is explained by the increase in the intergranular porosity, which reduces the mechanical strength of bio-based concrete. In addition, the increase of the vegetative particle content increases their specific surface area in the material. Consequently, this leads to a weak binder/aggregate bond [61] and a low compressive strength. Furthermore, it is also important to remember that the flax shives, which we consider as coarse aggregates in the concrete mix, do not carry any strength compared to the conventional coarse aggregates, hence the low compressive strength values recorded.

In general, the resistance sought depends on the application of the material in the building. Roof applications require high vegetative particle content and a small amount of binder. In this case, the material will have good thermal insulation with low resistance. Slab formulation contains a low dosage of vegetative particles with a high amount of binder, which gives it good mechanical strength. Between these two extremes, we find the wall formulation.

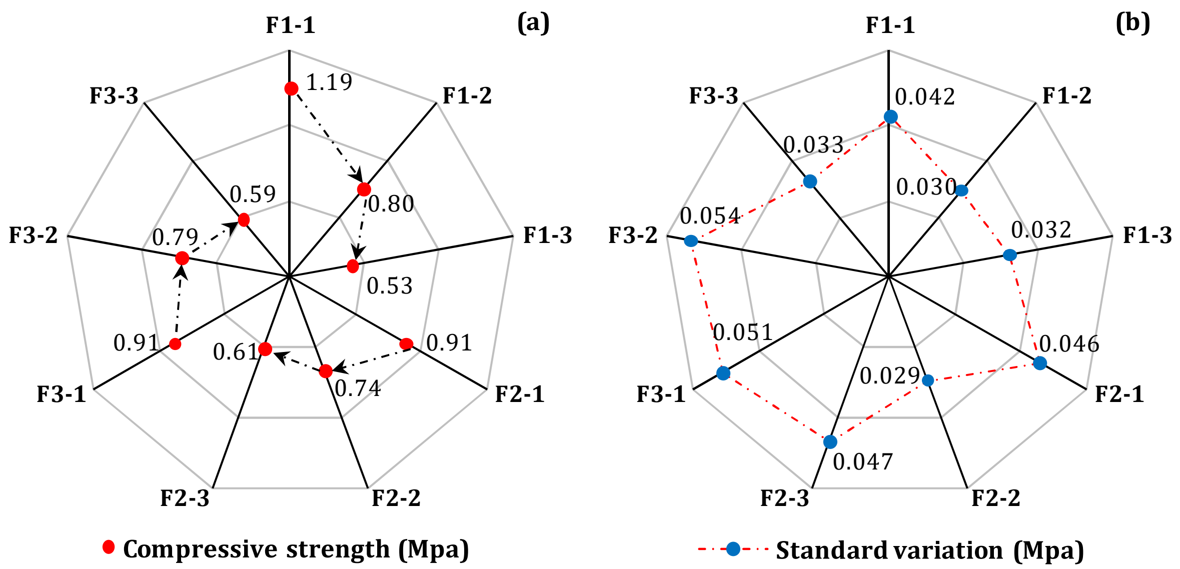

Figure 14. (a) Compressive strength of flax concrete, (b) standard deviations.

Furthermore, the effect of the size of flax shives on compressive strength appears to be negligible and not very pronounced, except for the F1-1 formulation, where the compressive strength is greater than the other formulations. This may be due to the orientation of the flax shives, in a direction that favours the compressive strength of the material.

4. Conclusions

This work presents an experimental investigation into the thermo-hydro-mechanical behaviour of a new bio-based concrete containing flax shives. For this purpose, nine types of flax concrete were characterised with several particle sizes and varied flax/binder ratio. The following conclusions can be drawn from this study:

- SEM observations have shown that flax vegetative particles have a complex and very porous microstructure. Several cracks were observed on the binder/flax particle interface. These were attributed to an eventual contamination of the flax shives particles and their hydrophilic property.
- Flax concrete behaviour is mainly governed by the quantity of flax shives constituting the material. We have shown that an increase in the amount of these vegetative particles leads, on the one hand, to an increase in porosity, moisture buffering capacity and maximum absorbed water content and, on the other hand, to a reduction in density, thermal conductivity and compressive strength. Furthermore, results showed that the size of the flax shives has very little influence in the overall hygrothermal performance of the material.
- Concerning insulation properties, we concluded that flax concrete has a low thermal conductivity, ranging between 82 and 127 mW/(m.K). In fact, the higher the flax shives content, the lower the thermal conductivity. In addition, this property slightly depends on the size of the flax shives but it depends on their arrangement and distribution in the material. A homogeneous particle size implies a slightly better distribution and, consequently, the microstructure will be less complex. This promotes the kinetics of heat transfer and reduces the insulating properties of the material.
- Sorption isotherms have shown the high adsorption capacity of flax concrete. At high relative humidity, the maximum water content absorbed and the moisture storage capacity increases with the amount of flax shives, while the particle size has no influence. In addition, the

sorption isothermal curves were accurately modelled (by the GAB model) with a minimum correlation coefficient of 0.995. This allows us to accurately reproduce the experimental results. Concerning the MBV, we have shown that it increases with the size and rate of flax shives in the material. The formulation having the highest flax shives content and a larger size yielded an excellent moisture regulating material with an MBV index of approximately 2.8.

- The compressive strength of flax concrete is closely related to the content of plant particles in the material. A high flax shives content implies an increase in porosity, which ultimately results in poor mechanical performance. In addition, an increase in the amount of flax shives reduces the particles/binder adhesion and then reduces the compressive strength. Recall that flax shives do not carry any strength compared to conventional coarse aggregates.

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