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Water Sensitivity of Hemp-Foam Concrete

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Abstract. The necessity to build energy-efficient and low environmental impact buildings favors the development of biobased light-weight materials as hemp-foam concretes. In this context, experimental protocols were developed to study the effects of hemp shiv and the production methods on the water sensitivity of bio-based foamed concrete (BBFC). Foam concrete incorporates several materials and compounds: cement, protein-based foaming agent, ground granulated blast–furnace slag, metakaolin as a binder, and hemp shiv as bio-based aggregates. The study investigated first the effect of the incorporation of hemp shiv (from 0 to 15 vol%) and then the elaboration method, comparing direct method versus preformed method on the resulting physical properties, the isotherms sorption-desorption and the capillary water absorption of hemp-foam concretes. We observe an increasing porosity of the concrete with hemp shives content. Additionally, hemp shives increase the adsorption and the capillary absorption of water. Moreover, the preformed method produces concretes more sensitive to water than the direct methods since it increases its porosities.

1 Introduction

Foamed concrete (FC) is a type of lightweight concrete produced by mixing foam with mineral mix, which has the properties of lightness, thermal insulation (Giannakou and Jones, 2002; Mohd Zahari et al., 2009) and fire resistance. Foamed concrete has been widely used as a heat conservation and backfill material in construction and road building (Amran et al., 2015; Hajimohammadi et al., 2018). Over the last decades, extensive researches has been carried out on the physical and mechanical properties of foamed concrete, in especially density, air-void structures and compressive strength (Fabien et al., 2019; Nambiar and Ramamurthy, 2007, 2006; Sebaibi et al., 2020; Visagie and Kearsley, 2002), as well as the properties of foaming agent (Panesar, 2013; Samson et al., 2012; Siva et al., 2017).

The high-water absorption of FC, especially ultra-light FC, tends to reduce strength, and decrease thermal insulation and durability performance. In addition, it increases the dry shrinkage and water absorption, which limits its wide development in the prefabricated insulation panel industry (Kearsley and Mostert, 2005).

Usually, the production of non-autoclaved foamed concrete is carried out by mechanical processes, using a foaming agent that generates foam before being added to the mix, called the preformed method, or by adding a foaming agent directly into the cementitious matrix, called the direct method (Samson, 2015). Generally, two types of curing are used to harden foamed concrete, i.e. autoclave curing and non-autoclave curing. However, the autoclaving step, at high temperature and pressure, considerably increases the production energy consumption (Amran et al., 2015). The associated grey energy is 340 kWh/m³, which corresponds to an emission of 168 kg of CO_2/m³. According to Couasnet (Couasnet et al, 2017), this grey energy is close to that of conventional concrete (≃ 500 kWh/m³), however, the elimination of autoclaving ensures the hardening of foamed concrete in the open air or in humid room. Therefore, the foamed concrete discussed in this document is not autoclaved and has been manufactured using the preformed foaming method.

As a highly porous material, FC is sensitive to water and humidity, which severely limits its wide application (Liu and Hansen, 2016; Medeiros and Helene, 2008; Tittarelli and Moriconi, 2010). Sun et al found that compressive strength of FC with a bulk density of 600 kg/m³ was reduced by 15-30% after 40 freeze-thaw cycles after immersion in water (Sun et al., 2018). Nambiar and Ramamurthy found that dry shrinkage of the FC was related to its moisture content, moisture loss may contribute to dry shrinkage of the FC (Nambiar and K, 2009). Chen et al found that the total weight of the FC with the bulk density of 550 kg/m³ would increase by about twice after water absorption, which significantly reduces the load capacity (Ma and Chen, 2016). Del Coz Diaz et al found that the thermal insulating performance of FC decreased with increasing moisture content of FC or decreased with increasing relative humidity of the environment (del Coz Díaz et al., 2013). Therefore, water repellent treatment of FC before application is essential for its long-term behavior.

Kearsley and Wainwright studied the porosity and permeability of FC and found that the water vapor permeability of this material increased with porosity and ash content (Kearsley and Wainwright, 2001). Sang and Falliano found that the bulk density decreased with the increase of porosity, and the volume water absorption rate increased with the increase of porosity (Falliano et al., 2019; Sang et al., 2015).

Most of the published research has also focused on the thermal and hygrometric qualities of hemp shiv concrete, due to the highly porous structure of hemp shiv (more than 75%) (Jiang et al., 2017; Tronet et al., 2016). The porous structure of hemp shiv gives hemp concrete a very high water absorption capacity, sometimes exceeding 300% by mass (Nguyen, 2010).

Hemp shives are widely used in concrete studies as an alternative to mineral aggregates. The valuable characteristics of hemp concrete are its light weight, excellent moisture absorption capacity, negative carbon balance, and low thermal conductivity which help to reduce building energy consumption (Chamoin, 2013; De Prez et al., 2018). Moreover, incentives are proposed the bio-based materials to play an increasingly important role in the composition of building materials (Ezziane et al., 2007; Page et al., 2015).

In this work, we study the effect of the incorporation of hemp shives (from 0 to 15 vol%) and the foaming method (direct and preformed) on the resulting density, porosity, isotherms sorption-desorption and capillary absorption of the foam concrete. The control foam concrete (without hemp shives) is formulated with 70 wght% cement, 20 wght% Ground-granulated blast-furnace slag and 10 wght% metakaolin with different admixtures.

2 Materials and Methods

2.1 Raw materials

A CEMI 52.5N Ordinary Portland Cement which fulfils all the requirements of EN 197-1 was used. Ground Granulated Blast Furnace Slag (GGBFS), a by-product from iron production according to EN 206-1, and Metakaolin (MK) obtained by kaolinite flash calcination at around 700°C are also used in this study. Hemp shiv (HS) as renewable vegetable raw material was used to reduce costs and CO_2 emissions. These raw materials are selected to prepare the bio-based foamed concrete (BBFC).

Table 1 lists the chemical compositions of CEM I, GGBFS and MK.

Tab. 1: Chemical composition of cement and pozzolans used in this study.

The chemical compound	Chemical composition (%)		
	CEM I (%) [a]	**GGBFS (%)** [b]	**MK (%)** [c]
Calcium oxide (CaO)	64.17	38.6	0.2
Aluminum oxide (Al_2O_3)	4.44	12.3	24.1
Silicon dioxide (SiO_2)	19.6	36.9	68.1
Ferric oxide (Fe_2O_3)	4	0.3	3.7
Sulfur trioxide (SO_3)	2.6	2.1	-
Sodium oxide (Na_2O)	0.07	-	0.1
Magnesium oxide (MgO)	1.25	7.5	0.2
Potassium oxide (K_2O)	0.84	-	0.4

[a] Data sheet of CEMI 52.5N cement manufactured by Calcia Cements.
[b] Data sheet of GGBFS manufactured by ECOCEM.
[c] Data sheet of Metakaolin manufactured by argeco developpement.

To obtain an acceptable workability of the mixture, a superplasticizer (SP) is used. In addition, a protein-based foaming agent (FA) that can withstand the formation of air bubbles is used, as well as an accelerator (Acc) to advance the hardening of the BFC to further stabilize the incorporated air bubbles. The density of the foam generated is approximately 70 kg/m³. The characteristics of each of these components are presented in Table 2.

Tab. 2: Characteristics of liquid-state admixtures used to elaborate the cementitious materials.

	Acc	**SP**	**FA**
State	liquid	liquid	liquid
Color	Yellow	brown	bright yellow
Density (g/cm³)	1,45 ±0,01	1,055 ±0,01	1,04 ±0,02
Recommended dose (%)	1-1,5	1-3	-
Chlorides content (%)	≤ 0,1	≤ 0,1	0,001
pH	6 ± 1	6 ± 1	9
Solids Content (%)	61,5 % ±2,7	30,5 ±1,5	30
Potassium oxide (K_2O)	0.84	-	0.4

2.2 Specimens elaboration

Two production methods are used in this study. Firstly, the preformed foaming method (Fig.1) is based on the separate production of a light and stable aqueous foam produced by mixing the diluted foaming agent with water in a ratio of 1:30 (by weight), mechanically, by a paint mixer. This aqueous foam is gradually inserted into a mineral suspension produced by mixing the mineral constituents and hemp shiv with water and admixtures until obtaining a homogeneous paste.

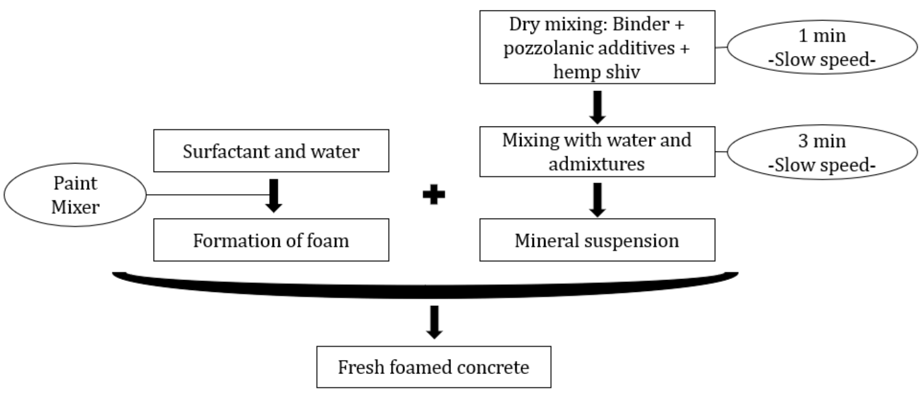


Fig. 1: Protocol of the preformed foaming method

Second, the direct method (Fig.2) is based on adding a foaming agent directly into the mixture and mixing all the compounds by a high-speed paint mixer. The preparation of the mineral mixture is the same in both methods.

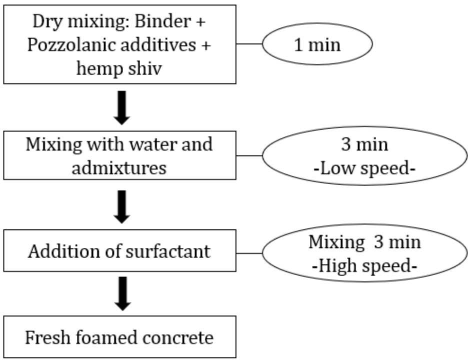


Fig. 2: Protocol of the direct method.

With both methods, the concrete obtained is fluid and foamy, and is placed without any vibration in eight cubed molds (15x15x15 cm³). These cubed samples are demolded and stored in a damp room (20 °C, RH > 95 %) after 48 hours curing at 20 °C. At 28 days, these samples are used to study the isotherm sorption-desorption and the capillary water absorption.

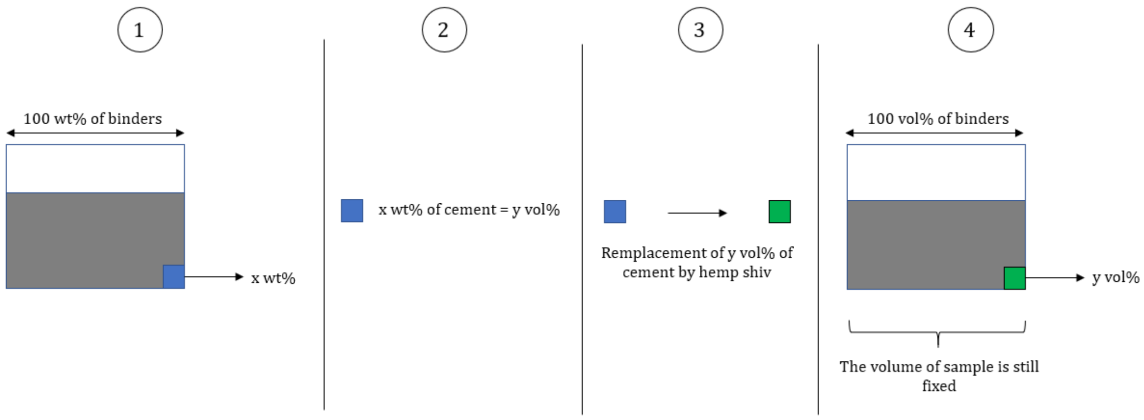


Fig. 3: Steps for the replacement of cement by hemp shiv with maintaining the volume.

The strategy used to formulate the samples in this study is to substitute the volume occupied by x wt% of the cement (5 and 15%) by hemp shiv, which means replacing the cement with hemp shiv and keeping the same total volume for all samples (Fig.3).
Therefore, the BBFCs are identified by CxHy in which C and H stand for Cement and Hemp shiv respectively. The respective amount x represents the weight percentage (wt%) of cement and y the weight percentage of cement replaced by hemp shiv. The "CxHy" label is followed by a production process letter, either P for “preformed method” or D for “direct method”. The composition of the different mixes is detailed in Table 3.

Tab. 3: Foam concretes composition [kg/m³].

Formulation	**Fresh density (kg/m³)**	**Composition of mixture (kg/m³)**							
		CEM I	**GGBFS**	**MK**	**HS**	**SP**	**ACC**	**FA**	**Water**
C70H0P	876	471	134.6	67.3	-	6.7	6.7	1.9	217
C65H5P	842	437	134.6	67.3	2.1	6.4	6.4	1.9	214
C55H15P	792	370	134.6	67.3	6.4	5.7	5.7	1.9	208
C55H15D	1278	1200	240	120	11.5	10.3	10.3	1.9	319

2.3 Tests methods

The fresh density is measured in a one-liter container with a measuring error of 20 kg/m³ according to NF EN 12350-6. Dry bulk density is measured in accordance with the NF EN 12390-1 standard by drying a group of three 15x15 cm cubic specimens at a temperature of 40 °C until the weight is constant; the weight/volume ratio becomes the density.
According to ASTM B923, the measurement of absolute density is investigated by AccuPyc II 1340 helium pycnometer. It allows accurate measurement of the solid phase volume of a known weight sample.
The water sorption/desorption isotherms were obtained using the dynamic vapor sorption method (DVS). This is a gravimetric technique for measuring the interactions of vapors with solids. ProUmid's SPS11-10µ was used for the DVS measurements on BBFC-samples. The measurements were performed at constant pressure and with a fixed total flow rate, in order to minimize the weight variations associated with the Archimedean force and the drag force. The use of a fixed temperature allows the isothermal sorption curve to be obtained by equilibrating the sample under a series of vapor concentrations. These curves are determined discontinuously in successive steps of increasing and then decreasing relative humidity (or vice versa), according to a method described in standard NF EN ISO 12571. The tests were carried out with representative samples of 1000 ± 100 mg which are automatically weighed every 20 minutes throughout the test. The relative humidity in the chamber varies between 10 and 90 %RH, in steps of 15% RH. For each moisture content, equilibrium is considered to have been reached when the change in mass of the samples is less than 0.01% in 120 minutes.
The water absorption by capillarity is based on NF EN 13057. This test consists of following the mass of the material whose underside is exposed to water (immersion depth of 2 mm) for the following immersion times: 5, 15, 30, 60, 120, 240, 1440, 2880, 5700 and 6600 minutes.

3 Results

3.1 Physical properties

The amount of porosity is related to the foam contents, water, binder and hemp shiv in the formulation (Nambiar and Ramamurthy, 2007). Moreover, porosity affects density, thermal conductivity, mechanical strength, durability and water absorption. According to NF EN 1097, total porosity is obtained from absolute density and bulk density according to the following equation:

$$\Phi = (1 - \frac{\rho_{bulk}}{\rho_{abs}}) \times 100$$

ρ_{bulk} : Bulk density (kg/m³).
ρ_{true} : Absolute density (kg/m³).

As shown in Table 4, the bulk densities of foam concrete made by the preformed method ranged from 608 kg/m³ to 691 kg/m³ with a high porosity between 70.7% and 74.5%. For direct method, the bulk density of C55H15D is approximately 1083 kg/m³ with a porosity of 54.6%.
Thus, the porosity of foamed concrete obtained by the direct method is lower than that produced by the preform method. The creation of air bubbles in the direct method is more difficult because the air bubbles are formed directly in the mineral suspension, which exerts a high pressure on the wall of the air bubble (Samson, 2015). The penetration of air into the cementitious suspension is thus more complicated than with the preformed method, where air void incorporated in the concrete is generated by mixing water and foaming agent and the cementitious suspension is then added to this foam. In addition, many factors affect the control of air bubbles production, such as speed, time and mixing directions.

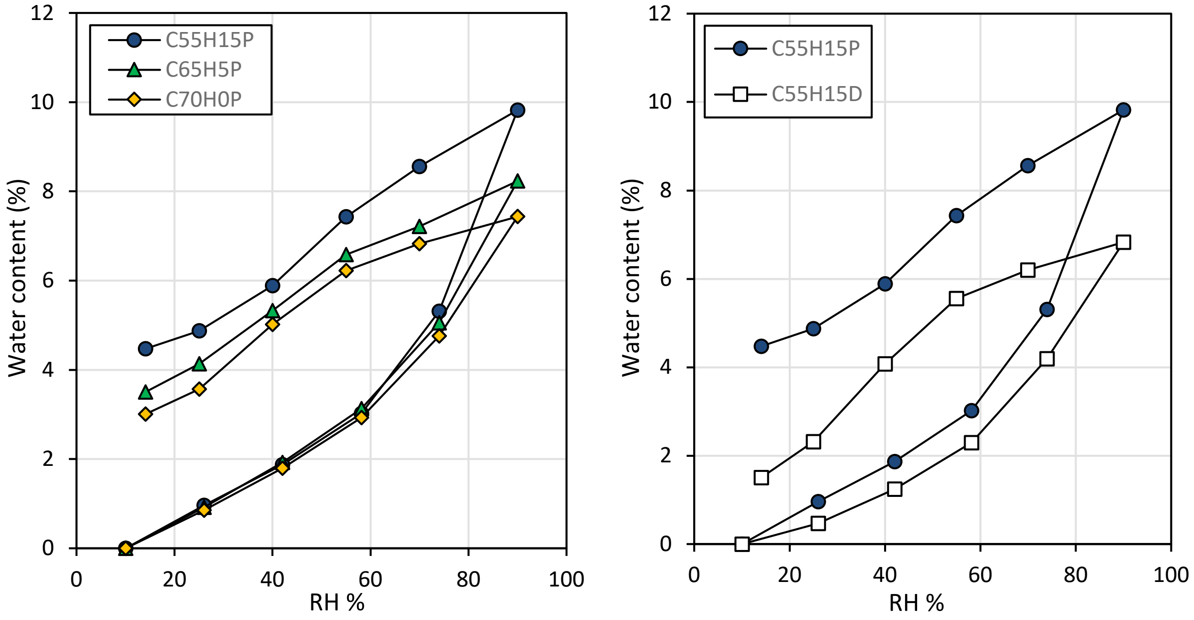
Tab. 4: Densities and porosity of all samples

Formulation	Absolute Density (kg/m³)	Bulk Density (kg/m³)	Porosity (%)
C70H0P	2386 ±98	691 ±22	70.7 ±1.3
C65H15P	2380 ±88	662 ±28	72.2 ±2.4
C55H15P	2361 ±130	608 ±32	74.5 ±2.1
C55H15D	2361 ±32	1083 ±19	54.6 ±0.9

As a conclusion from the comparison of the density and porosity of C55H15P, C65H5P and C70H0P, the porosity increases with the increase of hemp shiv (Table 4). Moreover, density is influenced by porosity, and increases with decreasing porosity and vice versa.
Besides, the constituents used in the formulation are also an important factor because the total density is affected by the absolute density of each constituent. Since the density of hemp shiv is very low, about 1400 kg/m³, the addition of hemp shiv decreases the density, therefore the foamed concrete density decreases as the quantity of hemp shiv increases.

3.2 Sorption-desorption isotherms

Figure 1 shows the isotherms obtained for the formulations in function of the quantity of the hemp shiv (a) and in function of the production method (b). The curves obtained are sigmoid. According to the IUPAC classification, the sorption curves could be classified as type II, while the desorption curves are type III. The results are consistent since these types of curves are usually obtained in macro-porous materials.



(a) (b)

Fig. 1: The isotherms of BBFC in function of: (a) the hemp shiv content, (b) the production method.

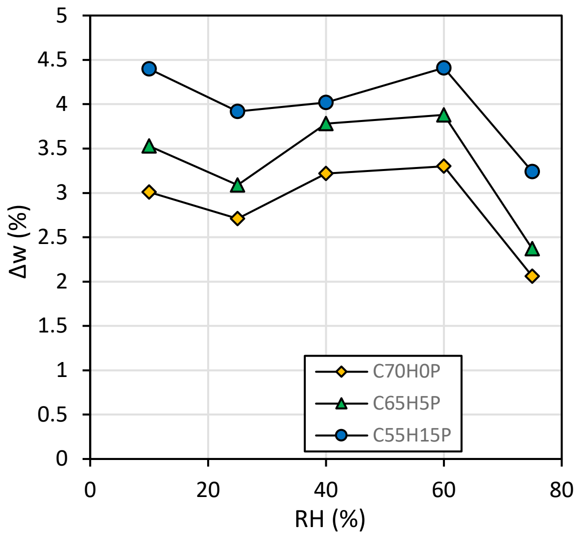
As shown in fig. 1 (a), at low and medium relative humidity, the water content in the sorption phase increases at the same rate for all 3 concretes. Moreover, at RH ≤ 80 %, the sorption curve is nearly identical, so at low relative humidity, the hemp shiv does not affect the hydric performance of BBFC. At the highest relative humidity levels, the water content of C55H15P rises significantly with increasing humidity. At 95% RH, the water content is 9.82%. In this range of humidity, capillary condensation is intense for C55H15P while it appears progressively for the others. During desorption, the hemp shiv increases the water retention capacity of the material since the water content of the individual hemp shiv increases with the surrounding humidity due to the highly hydrophilic character of all lignocellulosic materials, which brought about by their free hydroxyl bonds (Alix et al., 2012).

As shown in fig. 1 (b), at low and medium humidity levels, the change in water content of BBFC with relative humidity is lower with the direct method than with the preformed method. At higher humidity levels, the difference in water content between the two concretes increases sharply with humidity. At 60% RH, regarding the sorption curve, the difference between the two methods is 0.7%, increasing to 3% up to 95% RH. This difference is due to the difference in porosity in the materials (Chamoin, 2013; Glouannec et al., 2011).
In both figure (Fig.1 (a) and (b)), the end of the desorption branch does not close the loop, there is still an exposed water content. This difference in dry mass is explained by entrapped water as chemically bound water and other chemical reactions such as carbonation (Chamoin, 2013).

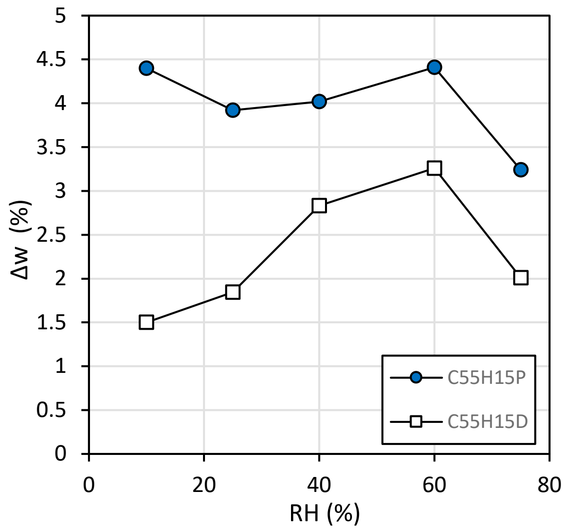
Tab. 5: Sorption-desorption rates and the weight difference values.

	RH (%)	10 %	25 %	40 %	60 %	75 %
C70H0P	Sorption (%)	0	0,85 ±0,03	1,79 ±0,05	2,92 ±0,09	4,76 ±0,15
	Desorption (%)	3,01 ±0,1	3,56 ±0,12	5,01 ±0,17	6,22 ±0,21	6,82 ±0,24
	Δw (%)	3,01	2,71	3,22	3,3	2,06
C65H5P	Sorption (%)	0	1,06 ±0,05	2,16 ±0,07	3,49 ±0,11	5,66 ±0,31
	Desorption (%)	3,53 ±0,09	4,15 ±0,12	5,94 ±0,23	7,37 ±0,41	8,03 ±0,32
	Δw (%)	3,53	3,09	3,78	3,88	2,37
C55H15P	Sorption (%)	0	0,95 ±0,02	1,86 ±0,08	3,02 ±0,18	5,31 ±0,18
	Desorption (%)	4,4 ±0,22	4,87 ±0,19	5,88 ±0,28	7,43 ±0,36	8,55 ±0,43
	Δw (%)	4,4	3,92	4,02	4,41	3,24
C55H15D	Sorption (%)	0	0,47 ±0,01	1,24 ±0,07	2,29 ±0,04	4,19 ±0,1
	Desorption (%)	1,5 ±0,04	2,31 ±0,08	4,07 ±0,09	5,55 ±0,1	6,2 ±0,07
	Δw (%)	1,5	1,843	2,83	3,26	2,01

The phenomenon whereby an absorbent contains more water during desorption than during sorption is called 'hysteresis' (Zhang, 2010). Figure 2 shows the evolution of hysteresis over the relative humidity. For all formulations, Δw presents its maximum value for a humidity of 60% in relation to the phenomenon of capillary condensation which tends to retain water in high quantities.



(a)



(b)

Fig. 2: The water content retained of BBFC in function of: (a) the hemp shiv content, (b) the production method.

Figure 2 (a) shows that the Δw increases with the increase in the amount of hemp shiv which increases the capacity of water conservation proving that the hemp shiv increases the adsorption surface of the material. While in fig. 2 (b) the direct method decreases the water retention due to the porosity and provides more hydric comfort than the preformed method since at 10%, C55H15D retains three times less water than C55H15P.

3.3 Capillary water absorption

Capillary water absorption is a reliable way of measuring the ability of a material to absorb and transmit water by capillary (Hall, 1989).

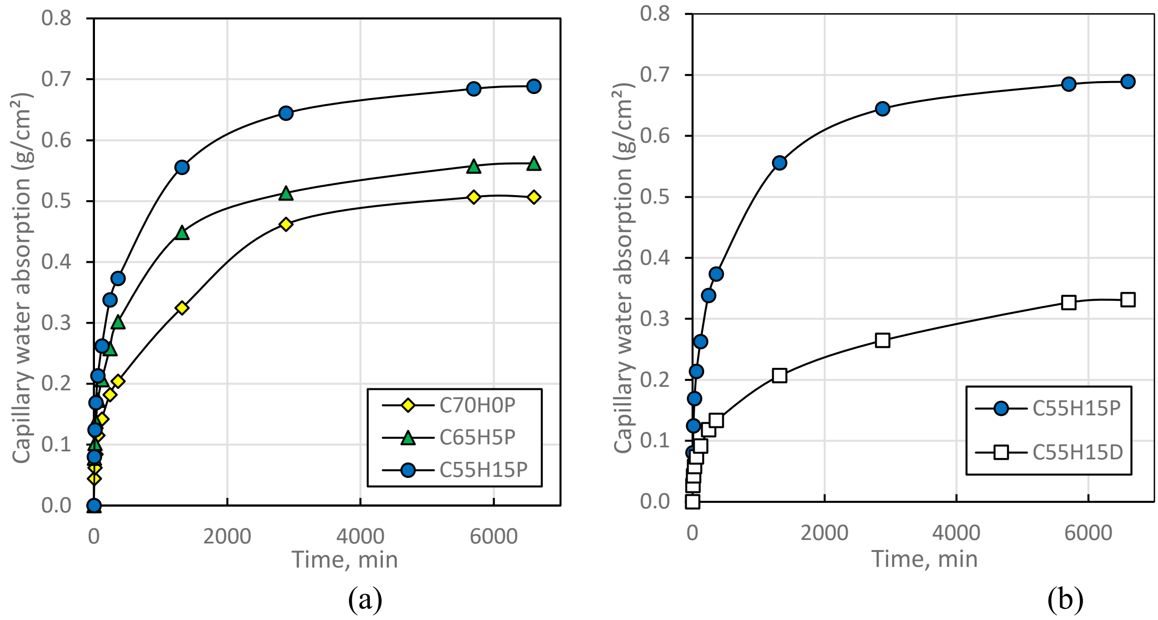


Fig. 3: Capillary water absorption of BBFC in function of: (a) the hemp shiv content, (b) the production method.

According to the curves in fig.3, the process of water absorption can be divided into two stages: rapid absorption and steady absorption. In the period of rapid absorption, the curves of water absorption are nearly coincident for the samples with different hemp shiv contents; this stage is mainly controlled by BBFC capillary pores (Bentz et al., 2001). At the end of rapid absorption, water penetrates the samples the samples through the capillary pores. After that, water continues to transport into gel pores, which is mainly controlled by the mechanism of diffusion (Martys and Ferraris, 1997).
Additionally, figure 3 (a) shows that capillary absorption of water increases with increasing hemp shiv due to its capacity of absorption of about 300% of its volume (Nguyen, 2010), and figure 3 (b) proves that the direct method decreases capillary absorption because it depends on the total porosity which is in accordance with the results of isotherms.

4 Conclusion

This paper has presented an analysis on the effects of hemp shiv and foaming method on the water sensitivity of foamed concrete starting from the physical properties up to the isotherms sorption-desorption and the capillary water absorption. Based on our experimental results, the following conclusions can be drawn:

- The density of bio-based foamed concrete (BBFC) decreases with the increase in the quantity of hemp shiv. The production method influences the volume of porosity in BBFC, the pre-formed method has a superior capability of embedding air bubbles in the cementitious matrix than the direct method.
- At the low and medium relative humidity, the hemp shiv has no effects on the adsorption of BFC, but at the highest relative humidity levels the adsorption increases significantly with the increase of hemp shiv quantity. Moreover, hemp shiv enhances the amount of water retained in the concrete. Additionally, the methods of production also affect the adsorption of BFC, the direct method decreases the adsorption more than the preformed method.

- Capillary absorption of water increases with increasing hemp shiv and the direct method decreases this absorption compared with the preformed method.

Besides, studying of a non-autoclaved bio-based structural and semi-structural concrete is in progress, in terms of mechanical, thermal and durability performances.

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