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▶ To cite this version:

Nicolas Massoni, Sophie Le Gallet, Lionel Campayo, Robert J. Koch, Scott T. Misture, et al.. Densification of non-radioactive porous siliceous particles loaded with cesium potassium copper hexacyano-ferrate by spark plasma sintering. Journal of the European Ceramic Society, 2021, 41, pp.1506 - 1513. 10.1016/j.jeurceramsoc.2020.10.024 . hal-03492742

HAL Id: hal-03492742 https://hal.science/hal-03492742

Submitted on 15 Dec 2022

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The use of pith in the formulation of lightweight bio-based composites: impact on mechanical and hygrothermal properties

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9 Abstract

10 The use of bio-based concretes or renders is rapidly developing. These sustainable materials present many advantages such 11 as their acoustical and hygrothermal properties. These bio-sourced composites are made of vegetable aggregates, 12 associated with a hydraulic binder. One of the most common aggregates is hemp shiv, which is an agricultural waste. 13 However, hemp shiv is not available in big quantities nor in all geographical areas, so it seems interesting to introduce other 14 bio-sourced aggregates in order to increase the availability. Sunflower and maize pith are unexploited agricultural by-15 products which can have a great potential as insulation materials. To use these aggregates, it is essential to assess first their 16 interactions with different binders. In the present paper, the impact of density and type of aggregate (either hemp shiv or 17 pith) on several key physical parameters was evaluated. These parameters were the uniaxial compressive strength test, the 18 thermal conductivity, the sorption isotherms and the water vapor permeability, as well as the moisture buffering value 19 (MBV). The use of pith shows promising results in terms of thermal and hygroscopic performances, the results also indicate 20 that specific precautions should be taken to preserve the porosity of the soft pith material to optimize the hygrothermal 21 performances.

22 Keywords: bio-based composites, hygrothermal properties, hydraulic binder, hemp shiv, sunflower and maize pith

23 1. Introduction

The building sector represents 20% of the final energy consumption in the world [1], 26.1% of the energy consumption in the EU and 27.9% in France [2]. The urge to reduce those emissions is becoming more and more a political issue, the recent conference of the parties on climate change organized by the United Nations reflects those preoccupations.

The building sector is currently facing major challenges, due to a growing concern on the energy consumption of buildings and its impact on the current climate crisis. A 2017 report by the UN Environment and International Energy Agency [3], reports the building sector being responsible for 36 % of the global final energy use. While the first challenge remains the reduction of energy consumption of the buildings during their use, the second challenge will be to reduce the embodied energy, in the building materials themselves and energy consumed during the construction phase.

34 One promising option to reduce embodied carbon in building materials is to favor locally sourced and 35 renewable materials [4]. Agricultural by-products become more and more used, some already have 36 established uses, such as hemp lime or the use of straw bales [5][6]. Many other agricultural by-37 products can potentially be used, research is ongoing worldwide to implement plant aggregates in 38 the formulation of light weight concretes or mortars [7][8]. Generally, such materials present good 39 qualities in terms of thermal insulation, even if large differences exist in function of density and 40 formulation. For example, [9] measured thermal conductivity for bulk hemp shiv with a density of 41 130 kg/m³ and obtained 54.5 mW/(m.K), as well as for sunflower pith with a density of 20 kg/m³, obtaining 50.9 mW/(m.K). These values are quite close to ones of synthetic insulation materials like 42 43 expanded polystyrene or glass wool, which commonly vary between 30 mW/(m.K) and 40 mW/(m.K). 44 Once mixed with a binder, those values do however increase, [10] found thermal conductivity values 45 oscillating between 117 and 138 mW/(m.K) for hemp composites of densities between 510 and

1 630 kg/m³. The same range of values was measured by [11][12][13] for hemp composites made with 2 lime and metakaolin and by [14] for maize and sunflower stalk based composites. In all these cases, 3 the sample densities were ranging between 500 and 600 kg/m³. [15] studied the impact on thermal 4 conductivity of the composition of two corn stalk and magnesium phosphate cement composites. 5 They noticed that samples with a higher corn stalk content had a lower thermal conductivity. [16] 6 found this same result on hemp composites, detailing however that the relation between the 7 amount of hemp shiv and thermal conductivity is not linear. Furthermore, [15] observed that for a 8 same corn stalk content, large stalks presented a lower thermal conductivity than small ones, which 9 was explained by a lower density and a higher porosity. Many parameters have an impact on thermal 10 properties of bio-based composites such as water content, density and the formulation. It has been 11 highlighted in the past that density has the biggest influence because a larger air volume in the 12 material results in a low thermal conductivity [10][15][16].

13 In addition to their promising thermal performances, bio-based composites are known to exhibit 14 good to excellent hygroscopic potential [9][17]. It traduces their ability to be used as a passive 15 humidity regulation system thanks to their high capacity of adsorption (and desorption) of water 16 vapor molecules from (to) the surrounding atmosphere. Due to the latent heat of adsorption and 17 desorption processes, these materials might also have the potential to be used as passive 18 temperature regulation system [11], even if the real impact of this effect on building energy 19 consumption still needs to be better assessed.

Other important assets of bio-based composites are their high vapor permeancy and their light weight, which make them suitable to be used to rehabilitate the national heritage, typically built in stone, adobe, rammed-earth, etc. [14][16][18]. Indeed, they do not constrict vapor exchanges between walls and their environment and they do not overcharge the existing structure.

24 On the other side, bio-based composites do not have mechanical performances as good as classic 25 building materials [10][17][19][20]. That is why they are most of the time rather used as filling and/or 26 insulation materials, for which a high loading capacity is not mandatory. Anyway, it is commonly 27 agreed that compressive strength and deformation modulus are good indicators of binder-aggregate 28 compatibility. The several studies led on these parameters lead to the conclusion that there is no 29 good or bad aggregate or binder, but good or bad combinations of them [21]. For example, [22] show 30 that a first composite made of corn stalk and ordinary Portland cement threw a 1.5 MPa compressive 31 strength value, while a second composite made of corn stalk and magnesium phosphate cement 32 presented a compressive strength more than two times higher (3.83 MPa). Another sound example is 33 given by [14]. In this study compressive strength at 60 days was measured on composites made of 34 lime and sunflower (LS) with a density of 540 kg/m³, metakaolin and sunflower (MS) with a density of 35 510 kg/m³ and finally, metakaolin and maize bark (MM) with a density of 530 kg/m³. These 36 composites developed a mechanical resistance of 0.21 MPa, 0.34 MPa and over 0.35 MPa 37 respectively.

Most of the time, the aggregate used in the formulation of bio-based composites is the hemp shiv. In France, for example, the soles professional rules that exist for this kind of materials are dedicated to hemp composite [5]. Nonetheless, it is essential to give alternatives to hemp [8][14][23] so as to have access to varied resources regarding geographical origin with the goal of reducing transport carbon print. For that purpose, a large variety of aggregates can be found, such as flax, straw, wood, coconut, miscanthus, corn or sunflower, etc. [18][19][24][25][26].

- 1 Based on this observation, this paper focuses on sunflower and maize pith, which, like hemp shiv, are
- 2 considered as agricultural by-products. Both sunflower and maize grow in most European countries
- and they already have been studied by some authors [14][23][27][28][29][30][31].

4 The binders used are lime based and contain cement and admixtures in certain cases. The goal is to 5 determine the impact of the use of pith instead of hemp on the performance of the composite. For 6 that purpose, two ranges of densities (low densities around 150 kg/m³ and medium densities around 7 500 kg/m³) and three binders are considered. Let us underline that it has already been determined in 8 a previous paper [32] that the geographical origin of the sunflower and maize piths does not impact 9 the performance of the composites. Their performance was assessed through their mechanical, 10 thermal, sorption and vapor transport properties. Thermal conductivity was studied through two different methods, the hot wire method and a novel device conceived for more accurate 11 12 measurement. Finally, the hygrothermal potentials of the composites were evaluated through the 13 moisture buffering test, and the consistency between results was analyzed using the MBV analytical 14 expression provided by [33].

Since hemp dominates the bio-based construction field and the regulations about vegetal composites are based on it, the aim of this paper is to determine whether maize and sunflower pith aggregates can be used at the same level, not to replace hemp but to provide more choice. In addition, the impact of the aggregate, of the binder and of the interaction of both will be assessed. We will as well determine whether used binders, which have originally been conceived for hemp shiv, are appropriate for maize and sunflower pith or not.

21 2. Materials

22 2.1 Plant aggregates

23 As part of this experimental campaign, three types of plant aggregates were studied: hemp shiv (H), 24 sunflower pith (S) and maize pith (M) (cf. Fig 1). The hemp shiv aggregates were received from an 25 agriculture cooperative based in the north of France. Loose hemp shiv aggregates had a density of 26 100 kg/m³, an average width of 4.1 mm and an average length of 7.6 mm. The sunflower pith comes 27 from an agriculture cooperative based in the south-east of France. Loose density of this sunflower 28 pith was around 14 kg/m³, an average diameter of the aggregates was around 4.2 mm. The maize 29 pith comes from an agriculture cooperative based in west France with a more oceanic climate. The 30 maize pith aggregates had a loose density of 18 kg/ m^3 , an average width of 2.2 mm and an average 31 length of 9.6 mm. The density of the aggregates has been determined following [34]'s protocol, 32 whereas the average aggregate dimensions have been calculated through a sifting granulometric 33 curve for pith and through a 2D image granulometric analysis developed by [35] for hemp shiv.



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Fig. 1. Aggregates used in this study (A) Hemp shiv, (B) Sunflower pith and (C) Maize pith

1 2.2 Binders

Three different types of binders were used in this study. The first one named C1 is a calcic lime based binder. The second one named C2, is a formulated lime which is composed of hydraulic lime, calcareous charges, hydrophobic and rheological admixtures. The last one, named HB, is a cement and lime mixture with further additives, this formulation was developed by an industrial partner and

6 whose exact composition is not available.

7 2.3 Bio-based composites

8 The samples were manufactured in the same conditions (50%RH and 23°C) and the main proportion 9 of the mixtures of all kinds of formulations used are summarized in **Table 1**. Samples were sprayed in 10 cylindrical formworks with a 16 cm diameter and a 32 cm height in a single layer except for C2-H*, 11 which was manufactured in 6 layers of about 5 cm each. Each layer was compacted at 0.05 MPa 12 following [5]. It is recalled that H, S and M are the aggregates explained in §2.1, more specifically 13 hemp shiv, sunflower pith and maize pith respectively, while C1, C2 and HB are the binders explained 14 in §2.2. C2-H* corresponds to a formulation that was compacted.

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 Table 1 Summary of the formulation and mass ratio.

Type of binder	C1	C2				НВ		
Type of	Н	Н	H*	S	H+S	Н	S	Μ
aggregates								
Designation	C1-H	С2-Н	C2-H*	C2-S	C2-H+S	HB-H	HB-S	HB-M
Hemp	0.33	0.33	0.33	0	0.17	0.33	0	0
shiv/binder** (-								
)								
Pith/binder** (-	0	0	0	0.10	0.06	0	0.20	0.16
)								
Water/binder**	0.81	0.88	0.88	0.80	1.07	0.88	2.92	2.92
(-)								
Mass	0.15	0.15	0.15	0	0.07	0.15	0	0
proportion of								
hemp shiv (-)								
Mass	0	0	0	0.05	0.03	0	0.05	0.04
proportion of								
pith (-)								

18 * corresponds to a formulation which has been densified using a tamper tool.

19 ** correspond to mass ratio between constituents

20 A pycnometer was used in order to determine the physical properties such as the skeletal porosity,

dry and skeletal densities of the different formulations according to the standard NF EN 1097-7 2008.
Results are shown in the **Table 2**.

Table 2 Summary of the physical characteristics.												
Formula tion	С1-Н	С2-Н	C2-H*	C2-S	C2-H+S	HB-H	HB-S	HB-M				
Porosity	0.76±0.0 2	0.79±0.0 1	0.70±0.0 2	0.77±0.0 1	0.70±0.0 2	0.78±0.0 2	0.94±0.0 1	0.92±0.0 1				
Dry density (kg/m³)	470 ±5	440 ±6	600 ±10	550 ±5	590 ±6	410 ±8	150 ±4	160 ±5				

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