Development of cellular construction material-based flax shives: Physico-mechanical and thermal characterisation

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Abstract. The reduction of energy consumption in construction, production of thermal insulation materials, and the solution of environmental problems by recycling by-product derived several industrial sectors are becoming greater problems. In this context, vegetable by-products are an excellent alternative product to substitute mineral aggregates because they are easily available and renewable low-cost raw materials, and have higher advantage for economy and environment concerns. The viability of using vegetable materials such as flax shives for developing a sustainable Lightweight Cellular Construction Material (LCCM) is investigated in this paper. The produced material containing different volumes of flax shives (0V (control specimen), 1V, and 2V) was lightened by creating a porous structure in the matrix through a chemical reaction between Aluminium powder and free lime from pre-formulated Tradical PF70 binder. A study conducted on hardened material properties has indicated a significant reduction in sample unit weight, thereby resulting in a level of compressive strength compatible with a load-bearing wall. The reduction in flexural strength was lower than that in compressive strength. This study has also highlighted the effect of the porous structure on the thermal conductivity that lead to provide a high degree of thermal insulation. These results show that the cellular material based on flax particle can be used as suitable insulated load-bearing walls.

1 Introduction

Innovative building solutions for conserving non-renewable resources have motivated extensive research to develop sustainable building materials based on easily renewable natural raw material resources. There is a growing interest in the utilisation of vegetable materials as aggregates and/or fibers reinforcement into lightweight composites called "green" composites/concretes for sustainable constructions. Various types of vegetable wastes (flax, hemp, coir, jute, bamboo, palm, kenaf, Diss,…), after being processed, have been used in shives form as replacement of sand and aggregates in concrete and mortars [1,2].Due to their many advantageous properties as their eco-friendly and economical characteristics, vegetable materials can adequately replace mineral aggregates in construction field [3,4]. These materials exhibit a high insulation capacity associated to a low density, and provide healthy living solutions, thanks to the vegetable materials ability to regulate humidity inside buildings by absorbing and/or releasing water, depending on the air conditions [5-6]. In France, among a wide variety of vegetable sources, a great importance is accorded to hemp shives for their applications in construction materials. Considering as by-products derived from Industrial hemp sector, these materials are becoming a major focus of the green housing segment because of their energy-efficient cultivation, and because hemp-based composites have no negative effects on human health [7]. The excellent physical and mechanical properties of hemp, including low density, high specific stiffness and strength, biodegradability, sound absorption, carbon-negative and non-toxic plant, predispose it for use in building materials (bio-composites) based on inorganic matrices [8], mainly for their application in the housing construction [9]. The panels based on hemp hurds with novel hybrid organic-inorganic binders characterized by their physical, microstructural, thermal, and mechanical properties have shown parameters comparable to those of commercially available products [10,11]. Although the demand for vegetable materials is growing worldwide, the specimen-based these plants need further research with respect to the opportunities for their use, and to provide novel products with improved properties. Another more innovative way is to develop new cellular specimen based on flax shives, in order to produce usable materials in cellular concrete applications. Through appropriate production methods, cellular concrete featuring a wide range of densities (300–1800 kg/m^3) may be obtained, in comparison with 2300 kg/m^3 for traditional concrete. A further innovative strategy is the lightened of the materials by creating a porous structure in the matrix through a chemical reaction between Aluminium powder and free lime. According to the researches down, these materials remain relatively unexplored. The scope of this study is

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to investigate the potential use of flax shives in Tradical PF70 hydraulic binder, within the scope of providing usable specimen in cellular concrete applications. The effect of different volume ratios of flax shives to binder of 0 (control specimen), 1, and 2 on physical (density, porosity), mechanical (compressive and flexural strengths), and thermal properties of specimen has been evaluated.

2 Materials and experimental testing

The vegetable particles used in this study are generated from waste by-products materials derived from linen industry. Resulting from flax fibres stripping process, these materials contain a mixture of flax shives, steam fragments, lint, and wood shaves. The shape and properties of used flax shives are shown in Fig. 1 and Table 1.

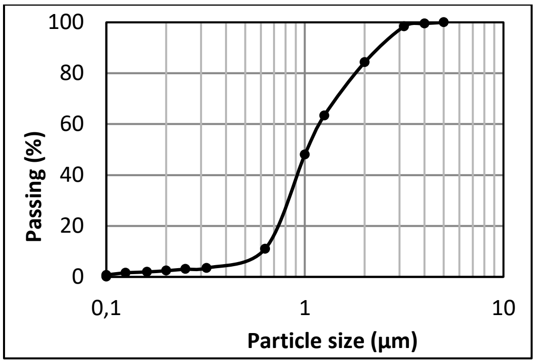


Fig. 1. Shape and particle size distribution of flax shives

Table 1. Properties of flax particles

Bulk density (kg/m^3)	Absolute density (kg/m^3)	Porosity (%)	Water absorption (%)
100 ± 15	1054 ± 35	90.5 ± 10	280 ± 25

Constituent materials mixes included Tradical PF70 binder manufactured by L'Hoist industry [12], Aluminum powder with 325 mesh in size and 99% purity, used for the lightening process, and flax shives added at different volume of 0 (Control Specimen), 1, and 2. The used amount of Aluminum powder in mixes is 0.3% by weight of binder. Both Tradical PF70-based binder and Aluminum powder were initially mixed in a planetary mixer. After mixing water adding, flax shives were uniformly dispersed with slow increment throughout the binder. The fresh materials were allowed to mix for free additional minutes. All the specimens were then casted on a vibrating table and moist-cured for 28 days at 20±2°C and 98% relative humidity. For hardened properties measurement, prism (40 x 40 x 160 mm), cylindrical (110 x 220 mm), and parallelepiped (250 x 250 x 60 mm) samples were prepared for compressive and flexural tests, and thermal conductivity measurement, respectively. Fig. 2 shows the expanded volume of fresh cellular specimen that occurred after 15 minutes of casting due to the chemical reaction between Aluminum powder and free lime. After 24h and before demoulding, the expanded part of hardened samples was cut off.

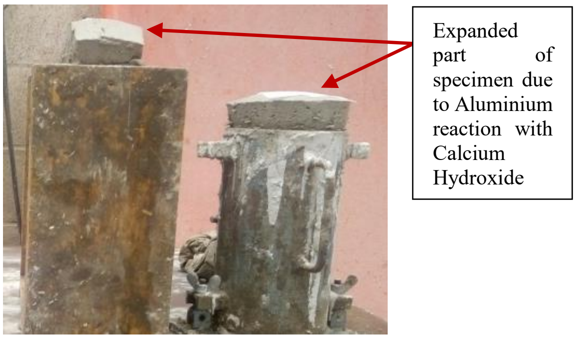
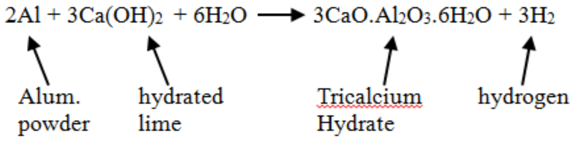


Fig. 2. Shape of expanded fresh specimen

The interaction occurred between Aluminium powder and Calcium Hydroxide of lime binder produces hydrogen gas, and thus creates microscopic air-bubbles in the matrix, according the chemical reaction mechanism of:



$$2Al + 3Ca(OH)_2 + 6H_2O \longrightarrow 3CaO.Al_2O_3.6H_2O + 3H_2$$

After 28 days of curing, the dry bulk density was measured, after oven-drying the samples at 60 °C, as determined by means geometrical measurement and weighting. The open porosity measurement was performed using the vacuum saturation method [13]. A dry sample of 40 x 40 x 60 mm in dimensions was placed in a desiccator and air was evacuated during several hours using a vacuum pump, then the water was injected until total immersion of the sample. As the material reached constant weight, the open porosity can be deduced by weighing in air and saturated mass obtained by hydrostatic weighing. The mechanical properties were evaluated by performing compressive and flexural tests in accordance with European Standard NF EN 196-1 [14], using an electromechanical testing machine SHIMADZU AG-IC model, equipped with a load cell of 250 kN. The loading rates of compressive and flexural-tests were 4 mm/min and 0.4 mm/min, respectively. Three replications were used for each property tested. The thermal conductivity was measured in dry state of sample by using the Guarded Hot Plate method (GHP), according to the standard ISO 8302 [15]. The thermal conductivity of specimens has been performed at different temperatures of 10, 20, 30, and 40 °C.

3 Experimental results and discussion

3.1 Specimen lightening

The effect of change in flax particles volume on dry unit weight of the specimen is shown in Fig. 3a. Value decreases from 1,080 kg/m^3, for control specimen (0 volume of flax), to 590 kg/m^3 for specimen with 2 volumes of particles. These values correspond to reduction of up to 44%. The decrease in unit weight is due to the physical properties of flax, since it has low density. In addition, the reaction between Aluminium powder and free lime creates porous structure that lightened the samples. Fig. 3b shows the air void structures of CCS compared to the CSF2 specimens. Uniform air voids distribution and part of continuous cells were observed in all specimen mixes. This indicates that the Aluminium powder used is highly effective in producing cellular specimen. Total porosity-values, measured by vacuum saturation, indicated that the increase of flax particles volume increases porosity of specimen. The values are shown in Table 2. The corresponding value increases from 28% to 69%. This contributes to lightening the material which make in the same magnitude of traditional cellular concrete in terms of density (300–1800 kg/m^3).

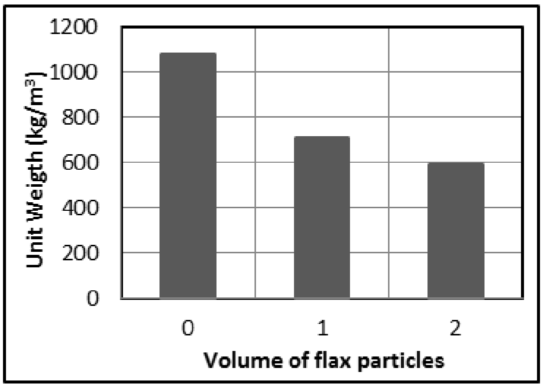
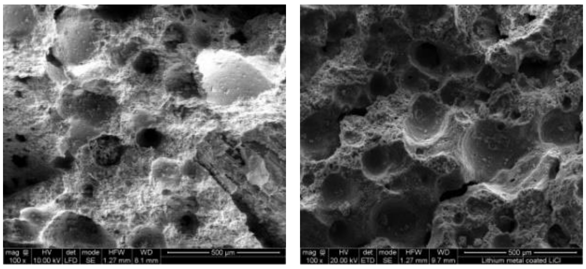


Fig. 3a. Sample dry unit weight vs. Flax volume



CCS sample CSF2 sample

Fig. 3b. SEM micrographs of cellular specimens

Table 2. Specimen properties

Specimen ID	Volume of flax particles	Open porosity (%)	Bulk density (kg/m^3)
CCS[a]	0	28	1,080
CSF1[b]	1	63	713
CSF2[c]	2	69	590

[a] Control Cellular Specimen ; [b] Cellular Specimen with 1 volume Flax ; [C] Cellular Specimen with 2 volumes Flax

3.2 Compressive strength of specimens

The 28-days stress-strain behavior of the specimens with respect to the flax particle content is presented in Fig. 4. The results indicated that the increase of flax particles volume serves to reduce compressive strength. Value de-creases from 1.52 MPa, for Control Specimen, to 0.74 MPa for specimen with 2 volumes of flax (CSF2). It corresponds to reduction of approximately 53%. The decrease in compressive strength is related to the mechanical properties of flax materials since they are less stiff than the surrounding hydraulic binder paste. The low strength of flax may be the important limiting factor affecting the specimen mechanical properties that leads to interfacial bond defects between particles and matrix. It is assumed that mechanical strength of specimen is opposite to its unit weight. In addition, the decrease in compressive strength is related to porous structure of sample. The more the air-bubble ratio, the lighter the specimen and the lower its mechanical strengths. The 28-days parameter-values of specimens, subjected to compressive test, are shown in Table 3. The corresponding elastic modulus-value varied from 353 to 212.5 MPa for CSF2 sample. The results highlight the ductile failure of the specimen-based flax particles that exhibits high plastic phase and underwent significant displacement before fracture. The ultimate strain-value varied from 6.95 mm/m to 12.55 mm/m.

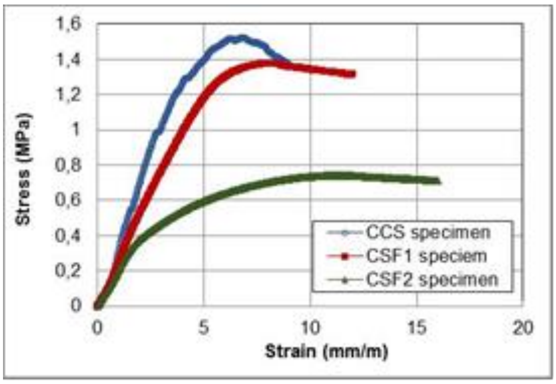


Fig. 4. Stress-Strain diagram of specimens

Table 3. Parameter-values of compressive-test

Specimen ID	Compres. Strength (MPa)	Ultimate Strain (mm/m)	Elastic Modulus (MPa)
CCS	1.52 ± 0.15	6.95 ± 1.12	353.0 ± 5
CSF1	1.38 ± 0.25	8.18 ± 1.53	242.4 ± 10
CSF2	0.74 ± 0.16	12.55 ± 1.65	212.5 ± 15

3.3 Flexural strength of specimens

The variation in 28-days load-deflection curves in flexural behaviour with different flax volume is shown in Fig. 5. A very low reduction in the flexural strength of the specimen is observed with particles adding. Value decreases from 1.18 MPa, for reference specimen, to 1.05 MPa for CSF2 sample with 2 volumes of flax. The value corresponds to reduction of up to approximately 11%. This finding suggests that both mechanical properties of particles and sample's porous structure decrease the mechanical strengths of specimen. Results also indicated that for a given flax ratio, the decrease in flexural strength is lower than that in compressive strength, probably due to the dilution effect of flax. It is considered that the tension effect of the flax particles occurs during the diffuse micro-cracking phase of "bending" the active micro-cracks and then in delaying the onset of their appearance, which serves to improve material flexibility. This may be also explained by the capability of flax particles to bridge the cracks and lead to limit their progression in the matrix. This bridge effect makes ductile material. The corresponding parameters, indicated in Table 4, show an increase in deflection with flax particles addition. The variation of elastic modulus confirms this tendency with decreasing the corresponding value.

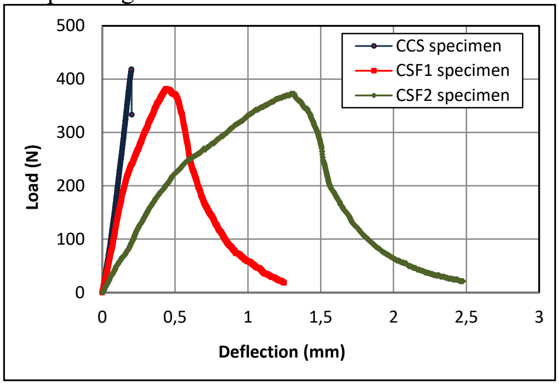


Fig. 5. Load-Deflection diagram of specimens

Table 4. 28-days parameter-values of flexural-test

Specimen ID	Flexural Strength (MPa)	Ultimate deflection (mm/m)	Elastic Modulus (MPa)
CCS	1.18 ± 0.12	0.20 ± 0.05	331.70 ± 5
CSF1	1.07 ± 0.26	0.43 ± 0.08	222.89 ± 8
CSF2	1.05 ± 0.28	1.29 ± 0.09	78.56 ± 9

3.4 Thermal conductivity of specimen

The effect of flax particles on thermal conductivity-value of specimens in dry state is indicated Fig. 6. It is clear that the increase in the vegetable particles volume decreases thermal conductivity as a result of lower unit weight of specimen. The value reduced from 0,315 W/mK, for CCS sample, to 0.184 and 0.143 W/mK for CSF1 CSF2 specimens, respectively. The decrease corresponds to 41.6%, and 54.6% for 1 and 2 volumes level of flax, compared with control specimen, respectively. The thermal conductivity of materials is affected by several factors, including their structure, material mixture proportioning, type of aggregate inclusions, density, porosity, etc.… The reduction in thermal conductivity of specimen is due to the insulating effect of flax particle, which has a lower value of λ = 0.15 W/m K [16]. It is evident from these results that the aggregates with less thermal conductivity produced the less conductive specimen. The porous structure of the materials also provides a high degree of thermal insulation. The thermal performances of the sample containing flax particles are related to the air-voids in the matrix that results in less unit weight. The more the air-bubbles ratio, the lighter the specimen and the lower its thermal conductivity. The investigation of conductive specimen as temperature ranged from 10°C to 40°C has shown in figure 7a. Thus, there is no significant variation in thermal conductivity for specimen with flax particles. It can be observed that the thermal conductivity varies linearly with the temperature. The increase of average temperature-test from 10 to 40°C, leads to increase thermal conductivity in the same way by approximately 4.5% for specimens with 1 and 2 volumes of flax. For Control Specimen, the increase is approximately of up to 23.5%. This trend indicates that the thermal conductivity does not depend exclusively on the conductive constituents, but also on its porous structure. Regarding the high amount of air-bubbles, present in the matrix, the increase of thermal conductivity of specimens is related to the increase of the conductivity of air with temperature [17,18].

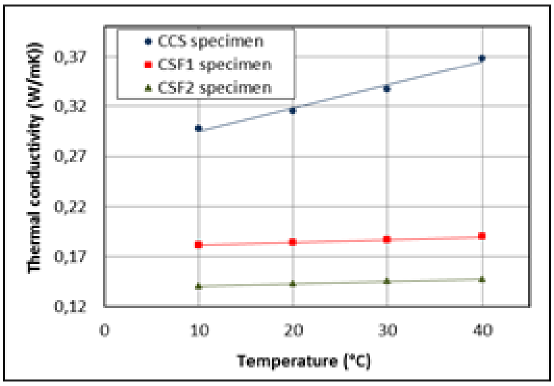


Fig. 6. Dry thermal conductivity-value vs. temperature for different specimens

4 Conclusion

A test program was conducted in this study to develop information about properties of cellular specimen based on flax particles. The test results indicated that there is great potential for the use of flax by-product in in binder mixes to produce lightweight construction materials usable in cellular concrete applications such as load-bearing wall materials. Results tests performed on hardened specimen have shown that the specimen reached a dry unit weight of about 590 kg/m3 with a compressive strength of 0.74 MPa. The reduction is related to both low stiffness of particles and porous structure of the specimen. The reduction in flexural strength is lower than that in compressive strength due to the bridging effect of flax particle. The investigation of conductive property highlights the thermal performances of the material with a value of 0.143 W/mK in thermal conductivity. Although the strength was reduced, the cellular material satisfies the basic requirement for load-bearing wall, according to the RILEM classification [19].

This research highlighted the effect of adding flax particles to attain substantial properties of innovative cellular materials and allows considering a broad range of applications in the field of cellular concrete. In spite of the positive implications of the test-results, supplementary research is required to examine the effect of varying porous structure level on physico-mechanical and thermal properties of the materials.

For further study, it is interesting to examine the hydraulic properties of this specimen.

References

1. D. Gavrilescu, B.M. Tofanică, A.C. Puitel, P. Pétrea, Sustainable use of vegetal fibres in composites. Sources of vegetal fibres. Environ. Eng. Manag. J., 8, 429–438 (2009).
2. R. Réh, Admixtures of non-wooden lignocellulosic matarials in combination with wood particles in composite materials. PRO LIGNO, 9, 519–524 (2013).

3. E. Sassoni, S. Manzi, A. Motori, M. Montecchi, M. Canti. Novel sustainable hemp-based composites for application in the building industry: Physical, thermal and mechanical characterization. Energ. Build., 77, 219–226 (2014).
4. S. Elfordy, F. Lucas, F. Tancret, Y. Scudeller, L. Goudet. Mechanical and thermal properties of lime and hemp concrete (hempcrete) manufactured by a projection process. Construct. Build. Mater., 22, 2116–2123 (2008).
5. D. Romildo, T. Filho, K. Ghavami, G.L. England, K. Scrivener. Development of vegetable fibre-mortar composites of improved durability. Cement and Concrete Composites, 25(2):185-196 (2003).
6. M. Merzoud., S. Sellami, A. Gouasmila, A Benazzouk. (2015), Effet du traitement des fibres de diss sur le comportement mécanique des composites cimentaires. Conférence Internationale Francophone NoMaD 2015 (Nouveau Matériaux & Durabilité), LGCGE-Ecole des Mines de Douai, Lille Nord de France (2015).
7. A. Evrard, A. De Herde, Hygrothermal performance of lime hemp wall assemblies, J. Build. Phys. 34, 15–25 (2010).
8. A. Benazzouk , O. Douzane, K. Mezreb, M. Quéneudec. Physico-mechanical properties of aerated cement composites containing shredded rubber waste. Cem. Concr. Comp., 28: 650–657 (2006).
9. P. Daly, P. Ronchetti, T. Woolley, Hemp lime bio-composite as a building material in irish construction, in: STRIVE Report 2009-ET-DS-2-S2, The Environment Protection Agency, Irland, (2012).
10. S.F. Santos, G.H.D. Tonoli, J.E.B. Melja, J. Florelli, H. Jr. Savastano. Non-conventional cement-based composites reinforced with vegetable fibers: A review of strategies to improve durability. Mater. Constr., 65, 317(2015).
11. Manzi, S.; Sassoni, E.; Motori, A.; Montecchi, M.; Canti, M. New composite with hemp hurds for sustainable buildings. Environ. Eng. Manag. J., 12, 31–34 (2013).
12. BCB, 2015, http://www.bcb-tradical.fr.
13. EN 196-1:2005. Methods of testing cement. Determination of strength properties.
14. NF P 94-410-3 "Roches. Essais pour déterminer les propriétés physiques des roches. Partie 3: Détermination de la porosité", mai 2001, ISSN 0335-3931.
15. Norme ISO 8302, Isolation thermique-détermination de la résistance thermique et des propriétés connexes en régime stationnaire - méthode de la plaque chaude gardée (1991).
16. R.J. De Dear, G.S. Brager, Thermal comfort in naturally ventilated buildings:revisions to ASHRAE standard 55, Energy Build. 34 (6), 549–561 (2002).
17. O. Krischer, W. Kast, Die wissenschaftlichen Grundlagen der Trocknungstechnik, 3. Auflage, Springer-Verlag, Heidelberg (1992).
18. B. Ruth, R. Ranyl, An investigation of the thermal properties of hemp and clay monolithic walls, in: Advances in Computing and Technology the School of Computing, Information Technology and Engineering, 5th Annual Conference, 163–170 (2010).
19. RILEM LC2. (1978). Functional classification of lightweight concrete. Materials and Structures, 11, 281–283.