

Physico-mechanical characterisation of construction materials based on agro-sourced particles: Hemp concrete

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Abstract. The study reported in this paper was undertaken to investigate the feasibility of lightweight construction materials, based on vegetable particles. The developed material consists of reference mortar containing different levels of hemp particles as partial replacement of sand in mixture by volume at: 0% (MR), 50%, and 100%. The binder nature has been selected based on the results obtained of chemical compatibility evaluation that highlight the reduction in inhibitory effect exerted by particles on cement hydration. The objective of this work is to evaluate the physico-mechanical properties, through the examination of materials lightning, mechanical strengths (compressive/flexural), and the elasticity behavior of the material at different volume rates of hemp particles. The influence of the direction after casting the material, according to the parallel (//) and perpendicular (\perp) orientations, with respect to the direction of the stress has been examined. Test-results have shown that despite a significant reduction in mechanical properties, the material exhibits higher residual stress that highlight a ductile behaviour, compared to the reference material. Results also indicated that the perpendicular (\perp) casting direction leads to exhibit higher mechanical properties, compared to the parallel state.

1 Introduction

The requirements of the new Building Regulations have obliged the engineers to develop alternative materials from renewable resources. Materials reinforced with vegetable fibres and/or particles are currently considered amongst the most promising materials in sustainable engineering technologies due to their several potential applications. In addition to its sustainable credentials, these materials exhibit a high insulation capacity associated to a low density [1,2]. The use of renewable raw material derived from vegetable products has been the subject of extensive research. Various types of vegetable wastes (flax, hemp, coir, jute, bamboo, palm, diss,...), after being processed, have been used in particles form as replacement of sand and aggregates in concrete and mortars [2].

Although all the mentioned advantages, the production of specimen materials reinforced with vegetable particles is limited by their long-term durability. The degradation problem is associated with an increase in vegetable materials fracture due to a combination of their weakening by alkali attack, related to their both mineralization and high water absorption [3,4]. This causes the material to have a reduction in post-cracking strength and toughness. In addition, their hydrophilic nature leads to a notable decrease in physical, mechanical and thermal properties and eventually rotting due to fungi attack. The role of vegetable materials as

reinforcement lies in the proper interfacial bond between the particles and the matrix as well as to ensure the durability of the specimen. To enhance the performances of vegetable particles, several approaches have been studied including particles impregnation with blocking agent and water repellent agent, sealing of the matrix pores system, reduction of the matrix alkalinity, and combination of particles impregnation and matrix modification [4].

The main objective of this study was to investigate the potential utilisation of hemp particles as partial replacement of sand in mortar at different levels: 0% (control mortar), 50%, and 100% by volume. In order to mitigate the inhibitory effect exerted by vegetable particles on cement hydration, amount of Tradical PF70 hydraulic binder has been used as partial replacement of Portland cement in the matrix. The performances of the materials have been evaluated by means of mechanical properties, such as compressive and flexural strengths, cracking behavior, ductility and Brittleness Index. However, the effect of fresh materials casting direction, according to the parallel (//) and perpendicular (\perp) orientation, with respect to the direction of the stress solicitation on the hardened mechanical properties has been also examined.

2 Materials and experimental testing

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2.1 Materials

The hemp shivs are ligneous particles extracted from the core of hemp stems (*Cannabis sativa*). The selected particles are derived from industrial defibration process. The properties and shape of hemp particles used are shown in table 1 and figure 1, respectively. It should be noted that the particles exhibit a high porosity, with an obvious high water absorption rate.

Table 1. Properties of hemp particles

Bulk density (kg/m ³)	Real density (kg/m ³)	Porosity (%)	Water absorption (%)
120,5	1460,5	91,7	241,8

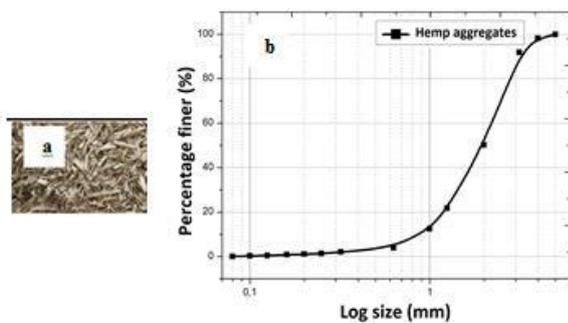


Fig. 1. (a) : Shape of hemp particles ; (b) : Grading size curve

Constituent materials for cement composite mixes included a type II CPJ 32.5 Portland cement according to Standard NF P 15-301 [5] requirements, Tradical PF70 binder [15], and natural sand with 4 mm maximum size. Hemp particles were added as a partial replacement of sand in control mortar specimen with proportions of 0.7:0.3:3:0.6 by weight of cement, Tradical PF70 binder, sand, and water respectively.

Both cement and Tradical PF70 binder were initially mixed in a planetary mixer. After mixing water adding, vegetable particles were then uniformly dispersed with slow increment throughout the binder. The fresh materials were allowed to mix for three additional minutes. All the specimens were compacted on a vibrating table and moist-cured for 28 days at 20±2°C and 98% relative humidity. For hardened properties measurement, prism, cubic, and cylindrical samples of 70 x 70 x 280 mm, 100 x 100 x 100 mm, and 110 x 220 mm in size were prepared for flexural and compressive tests, respectively. For each composition, the cubic specimens have been tested in the parallel (//) and perpendicular (⊥) orientation, with respect to the casting direction. Figure 2 shows the two configurations.

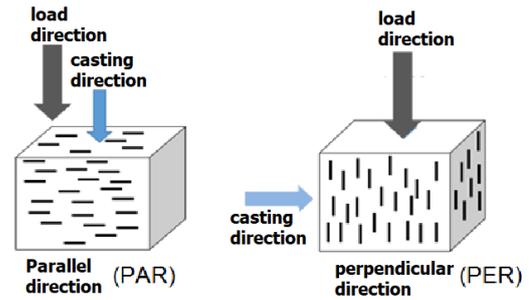


Fig. 2. Schematic representation of the solicitation direction, compared to casting process

2.2 Materials

The inhibitory effect exerted by hemp particles on the hydration reaction of binder was evaluated through hydration-test under the methodology described by Moslemi et al. (Figure 3a) [6]. The tests were conducted in order to select optimum binder composition that highlights low inhibitory effect. The experimental set-up is shown in Figure 3b. The test was performed by adding 10% and 30% of hemp particles by volume to an identical quantity of binder-water mixture that has been used as reference material. The effect of Tradical PF70 hydraulic binder used as 25% partial replacement of Portland cement has been also evaluated. The chemical compatibility was evaluated by means the inhibitory index *I* (%), using Eq. (1) [6].

$$I(\%) = 100 \cdot \left(\frac{t' - t}{t} \right) \cdot \left(\frac{T - T'}{T} \right) \left(\frac{a - a'}{a} \right) \quad (1)$$

where *T* and *T'* (C) are the maximum hydration temperatures of neat cement and the mixture, respectively; *t* and *t'* (h) are the times to reach maximum hydration temperature of neat cement and the mixture; and *a* and *a'* (C/h) are the maximum slopes of neat cement and the mixture, respectively. However, the smaller the *I*-value the higher the compatibility between binder and particles addition.

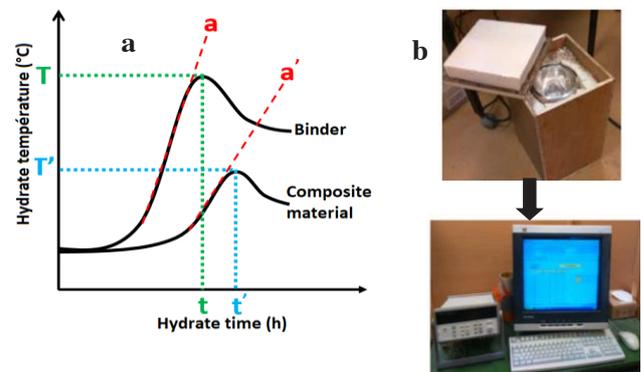


Fig. 3. (a): Hydration-test diagram ; (b): Hydration test set-up

The properties tested on the hardened specimens included dry unit weight, and compressive and flexural tests according to Standard EN 196-1 [7], using an electromechanical testing machine SHIMADZU AG-IC

model 250 kN. Three replications were used for each properties tested.

The compressive stress-strain curves have been recorded to evaluate the variation of ultimate strain, elastic modulus, and ductile and/or brittle nature of the specimens through the Brittleness Index (*IF*), as stipulated by Eq. 2. The correspondent stress-strain schematic diagram is shown in figure 4 [8].

$$IF = 1 - \frac{\sigma_{res}}{\sigma_{max}} \quad (2)$$

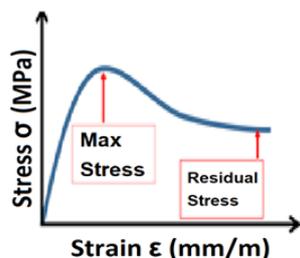


Fig. 4. Brittleness Index-value determination [8]

σ_{res} and σ_{max} are the residual and maximum stress, respectively. *IF* tends to 1, the specimen is Brittle; *IF* tends to 0, the specimen is Ductile.

3 Experimental results and discussion

3.1 Hydration test

Figure 5 shows the variation of the hydration temperature vs. time of specimen containing different levels of hemp particles, for two types of binder (100C/0T and 75C/25T). The data obtained from hydration curves, are listed in table 2. The addition of hems particles to cement clearly reduced maximum temperature attained and took longer time to achieve this maximum temperature, as compared to the neat control cement (100C/0T). Table 2 shows that the maximum temperature decreased from 64.9°C to 28.6 ° C, for hemp level varied from 0 to 30%. The corresponding times required to reach these temperatures, increased from 14.5h to 25h. These results suggest that the hemp material exerted a certain inhibitory influence on the cement setting. The corresponding inhibitory index (*I*) of 39% can be classified the material as "moderate inhibition". The same tendency was observed for specimen containing 25% of Tradical binder, as cement replacement (75C/25T). For specimens containing 30% of hemp particles, the corresponding inhibitory index-value of 9.5% classifies the mixture as being of "low inhibition", with lower value of time to reach maximum temperature, in comparison to specimen with 100C/0T binder. However, the test-results highlight the effect of Tradical addition on the reduction of inhibitory level exerted by hemp particles when hydration reaction occurs. The inhibitory effect is due to the chemical constituents of vegetable particles, but the main inhibitors of cement hydration are sugars and lignin [6]. Inhibition of cement occurs when the calcium silicate hydrate nucleation sites, on the originally positively

charged surfaces, are poisoned by the sugar-acid and lignin anions [9,10]. The difference observed between the specimens is related to the presence of lime in the Tradical binder, which generates Ca²⁺ ions in excess that are responsible for the material setting and hardening.

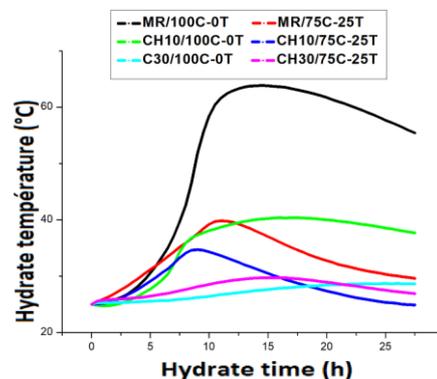


Fig. 5. Temperature / time hydration curve of different specimens

Table 2. Parameters of the hydration reaction

Binder	Hemp (%)	Temp Max. (°C)	Time Max. (h)	Initial setting time (h)	<i>IF</i> (%)
100C/ 0T	0	64,9	14,5	1,0	-
	10	40,4	17,0	3,2	3,2
	30	28,6	25,0	3,5	39
75C/ 25T	0	39,8	11,0	1,4	-
	10	34,6	9,0	2,1	0,3
	30	29,7	15,5	2,5	9,5

3.2 Physico-mechanical Properties

3.2.1 Material lightening

The hardened dry density of material vs. hemp particles is shown in table 3. Value decreases from 1,480 kg/m³, for MR specimen, to 820 kg/m³ of specimens containing 30% hemp particles replacement. The obtained values correspond to reduction of up to 44.5%. The decrease in dry density of specimen is due to the physical properties of particles, since they have lower density than sand materials. In addition, air-entrapped in in the matrix and higher open porosity as measured by water saturation procedure in specimen contribute to lightening the material. The corresponding porosity-value increases from 8.4% to 44.5% (table 3). The reduction in unit weight is very attractive particularly in the design of lightweight structural elements.

Table 3. Material properties

Material	Entrapped-air (%)	Open porosity (%)	Bulk density (kg/m ³)
MR-75C/25T	2.6	8.4	1,480
CH50-75C/25T	7.0	16.2	1,350
CH100-75C/25T	13.0	44.5	820

3.2.2 Compressive strength of specimens

The mechanical properties-values obtained for different cylindrical specimens are shown in table 4. Results indicated that the increase of hemp particles level leads to decrease compressive strength. Value varied from 9.2 MPa for reference mortar (MR-75C/25T), to 0.7 MPa, for a specimen with 100% hemp replacement of sand (CH100-75C/25T, which corresponds to reduction of approximately 92%. It is assumed that mechanical strength of specimen is opposite to its unit weight. The reduction in compressive strength is due to the low stiffness of hemp and also to the interfacial bond defects between particles and matrix. In addition, the decrease in compressive strength is related to porous structure of sample. The more the air-voids ratio, the lighter the specimen and the lower its mechanical strengths. In terms of bonding, the SEM micrographs of interfacial zone surfaces of hems particles/matrix, indicated that the bond appears to be lower (figure 6). The corresponding elasticity modulus-value varied from 2161.4 MPa for MR-75C-25T specimen to 54.3 MPa for CH100-75C-25T specimen. The elastic behavior of specimen has been characterised by Brittleness Index (*BI*), through stress-strain diagram for all specimens. Table 4 indicates that de *BI*-value varied from 0.82 for control specimen to 0.5 for specimen with 100% hemp particles. These results highlight the ductile failure of the material based on hemp particles and exhibits high plastic phase and underwent significant displacement before fracture, which was of a gradual shear type and not highly-cracked. The ultimate strain-value varied from 4.1 mm/m to 13.2 mm/m.

The influence of the material's casting direction, with respect to the compressive strength of cubic specimen is shown in figure 7. It can be observed that the specimen with PER (\perp) casting mode exhibits higher compressive strength, compared to the PAR (\parallel) casting direction. For specimen with 100% hemp particles, the compressive-values are 1.2 MPa and 0.7 MPa, for casting in PER and PAR direction, respectively. The difference observed is probably due the variation in the porosity at the interfacial zone between particles and matrix. The nature of the porosity at the interface, which is in deep form in the PER case, could contribute to improve the mechanical performances of the material.

Table 4. 28-days parameter-values of compressive test (Cylindrical specimen)

Material	σ_{max} (MPa)	Ultim. Strain. (mm/m)	Elast. Modulus (MPa)	σ_{res} (MPa)	<i>IF</i>
MR-75C/25T	9,2	4,1	2161,4	1,60	0,82
CH50-75C/25T	3,6	5,6	888,0	1,3	0,63
CH100-75C/25T	0,7	13,2	54,3	0,3	0,50

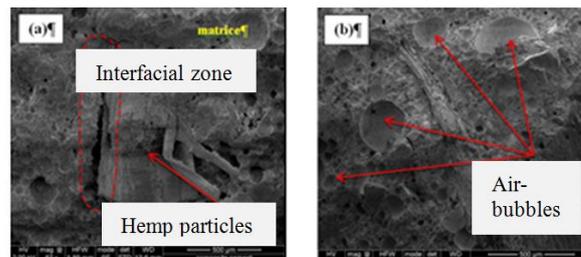


Fig. 6. SEM views of the state of materials

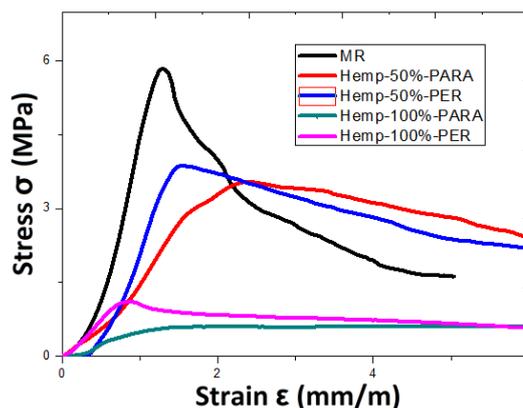


Fig. 7. Stress-strain diagram for PAR and PER casting (cubic specimens)

3.2.3 Flexural strength of specimens

The influence of the hemp particles on flexural behavior of specimens is illustrated by load-deflection diagram for different casting mode (figure 8). The corresponding parameter-values are listed in table 5. The results highlight a loss of mechanical performances, with the addition of hemp particles. For hemp ranging from 0 to 100%, the flexural strength varies from 3.74 MPa for MR-75C/25T specimen to 0.92 MPa, for CH100-75C/25T sample; It corresponds to performance-losses of up to 75%. Table 5 also shows that the material exhibits higher ultimate deflection under loading. Value varied from 0.17 mm/m to 0.33 mm/m with elastic modulus-values of 2121.2 MPa and 281.8 MPa, respectively. Despite higher flexural strength in the case of PER casting mode, the corresponding deflection is lower than the PAR casting orientation. Nevertheless, for 100% hemp replacement, the deflection is almost similar for the two types of casting.

The flexural strength reduction is due to both mechanical properties of hemp particles and porous structure of the matrix effect. Results also indicated that the decrease in flexural strength is lower than that in compressive strength, probably due to the dilution effect of hemp particles on the high deflection under loading of specimen. This may be due to the presence of particles which allow more particles to bridge the crack and lead to limit the progression of the cracks in the matrix.

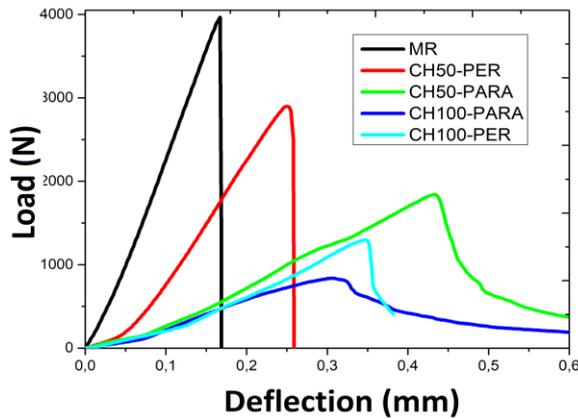


Fig. 8. Load-Deflection diagrams of materials in flexural test

Table 5. 28-days parameter-values of flexural test

Material.	σ_f (MPa)		Deflection (mm)		Elasticity modulus (MPa)	
	PAR	PER	PAR	PER	PAR	PER
MR 75C/25T	3,74		0,17		2121,2	
CH50 75C/25T	1,74	2,70	0,42	0,26	1262,4	391,2
CH100 75C/25T	0,92	1,32	0,34	0,35	281,8	286,7

Conclusion

The work presented herein focuses on the optimization of the hemp specimen formulation. The effect of different parameters such as hemp level and casting mode direction on the physic-mechanical properties has been examined. Test-results of fresh materials highlight the effect of Tradical binder addition on the decrease of inhibitory effect that has been exerted by hemp particles when cement hydration reaction occurs.

Test-results of hardened specimen have shown that the lightening of the sample, due to the hemp particles addition, induced significant reduction in mechanical strengths. The decrease in flexural strength is less important than to the compressive strength. This may be due to the presence of hemp particles that lead to limit the progression of the cracks in the matrix, due to the bridging phenomena. Results also highlight the ductile failure of the material based on hemp particles that exhibits high plastic phase and underwent significant displacement before fracture.

The study of the effect of casting mode, have shown that the PER (\perp) mode leads to increase both compressive and flexural strengths. The magnitude of the strain was also improved in this mode (PER), for the compressive-test, but decreased for flexural solicitation. This may be due to the bridging effect of particles that increase the ultimate deflection of the specimen in PAR (\parallel) casting mode.

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