Towards the enhancement of mechanical properties of Bio-Based Concretes.

Rafik Bardouh[1], Omayma Homoro[1], Sofiane Amziane[1],
[1] Clermont Auvergne INP, Institut Pascal UMR 6602 – UCA/CNRS, 63178 Aubière,

Abstract

In recent decades, great interest has been directed towards vegetable concrete due to its interesting hygrothermal and acoustic properties. One of the main scientific limitations of this type of concrete is its poor mechanical properties. An innovative way of reinforcement by the aim of FRCM (Fabric Reinforced Cementitious Matrix) has been applied to address the problem of weak mechanical properties. Two different methods of reinforcement were applied: (i) Bending reinforcement through a composite sandwich, where the vegetable concrete formed the core of the sandwich and the FRCM formed the skins of the sandwich; and (ii) compressive reinforcement by confining vegetable concrete cylindrical specimens by FRCM. The effect of reinforcement rate and textile pre-impregnation was evaluated in the case of bending reinforcement.

Huge improvements in mechanical properties were reached with both reinforcement techniques. For instance, the maximum load capacity increased by 17530.4 % in the case of sandwich specimens compared to reference vegetable concrete. On the other hand, again increase of 257 % was obtained in the maximum compressive strength for the confined cylinders compared to reference vegetable concrete. The obtained results were promising and open new perspectives in the field of reinforcement of plant-based concretes.

Keywords: FRCM, Plant-based concrete, Reinforcement, Mechanical properties, Pre-impregnation

I. INTRODUCTION

In France, 43% of energy consumption and 25% of greenhouse gas emissions are attributed the building sector, half of them related to building materials and equipment [1]. As a result, the reduction of the environmental impact of the building sector, particularly in terms of energy costs, has made the choice of building materials crucial. Previous researches have demonstrated the effectiveness of Bio-based materials in reducing the energy consumption due to their low embodied energy apart from carbon sequestration. [2]. Vegetable concrete can be made by using several plant aggregates such as hemp shives, flax shives, sunflower, coconut coir, wood chip, cereal or oilseed straws, rice husk, corn cob, diss stem, bamboo stem, cane bagasse, sugar beet pulp, miscanthus stem, and lavender straw incorporated with different mineral binders[3]. However, the most common type of vegetable concrete that has been introduced in the literature is the hemp-lime concrete. Hemp shives which constitute the woody porous part of the hemp stalk were characterized by highly porous structure due to their low density (around 50 kg/m^3), strong capillarity effects as they are able to absorb a high quantity of water up to five times their weight [4].

Hemp-lime concrete is the most sustainable low carbon green composite due to the lime carbonation which absorbs CO_2 from atmosphere and hemp carbon sequestration as they store carbon during their growth according to photosynthesis. [5] These two effects enable hempcrete to store approximately 35 kg of CO_2 per square meter of wall built with a thickness of 26 cm over 100 years [6]. The major drawback encountered with the use of green concrete in building structures is their low mechanical properties compared to conventional building materials. Available results of compressive tests on hemp concrete detect that the strength of hemp concrete is lower than 1 MPa, which makes this material too weak for structural use [7].

Several treatments were performed in order to enhance the mechanical properties of green concrete. These treatments were focusing on improving the chemical compatibility between the constituents of green concrete by series of lignocellulosic aggregates modification [8], mineral binder modifications [9], or by the interstitial zone between aggregates and cement. [10]

However, these treatments did not significantly lead to the enhancement of the overall mechanical properties of hemp concrete.

On the other side, Fabric Reinforced Cementitious Matrix or so called “FRCM” have been widely studied in the literature [11]. FRCM are a composite structures composed of a mineral matrix and a continuous fabric [12]. They have a very good mechanical properties and were successfully used to reinforce and/or to repair concrete and masonry structures [13]. Therefore, the objective of this paper is to propose a prospective solution to improve the mechanical properties of hemp concrete by reinforcing it with a composite material called FRCM (Fabric Reinforced Cementitious Matrix).

II. MATERIALS AND METHODS

II.1. Materials

II.1.1 Hemp shives

The bio-aggregates used in this study are the hemp shives. Several characterization tests were carried out in the laboratory to determine the physical and hygrothermal properties of the woody by-products which are listed in Table 1.

Table 1: Physical and Hygrothermal properties of Hemp shives.

Bulk density (Kg/m3)	112
Water retention capacity (%)	225
Dust content (%)	1.35
Thermal conductivity (W/ (m.k))	0.048

II.1.2 Calcium sulfo-aluminate cement

The Calcium sulfo-aluminate (CSA) cement was the mineral binder used in the manufacture of sandwich specimens (hemp concrete and FRCM). CSA cement consists of a mixture of 82 % sulfo-aluminate clinker and 18 % Anhydrite. One of the main reasons for using CSA cement is its ability to provide a lower alkaline medium due to the ettringite formed during the hydration mechanism, as shown in the following equation,

$$C_4A_3\check{S} + 2C\check{S} + 38H \rightarrow C_6A\check{S}_3H_{32} + 2AH_3 \quad \mathbf{(1)}$$

In this work, the W/C ratio of the CSA mixture used for FRCM and hemp concrete was 0.35 and 0.93, respectively.

The tensile properties of the CSA matrix were characterized by three-point bending tests on three prismatic specimens of 40 × 40 × 160 mm3, following the French standard NF EN 196-1. The average bending stress obtained after 28 days of curing was 5.6 MPa (COV 12%).

II.1.3 Prompt Natural Cement

The Prompt natural cement (PNC) was the mineral binder used in the manufacture of the confined cylindrical specimens. One of the main benefits behind using PNC matrix is its low environmental impact, as it reduces CO_2 emissions by 20% compared to Portland cement. in this work, the W/C ratio of the PNC mixture used for the FRCM and hemp concrete was 0.5 and 0.93, respectively. For a W/C ratio of 0.6, the compressive strength and Young's modulus of the PNC matrix after 28 days of aging are 10 MPa and 20 GPa, respectively.

II.1.4 Flax textile

The reinforcing element used in this study was the unidirectional flax textile issued by Bcomp. The mechanical properties of this textile at dry conditions were determined by performing a direct tensile test according to ISO 13934-1. The average tensile strength and Young's modulus of flax textile were 123MPa and 7 GPa, respectively.

II.2 Specimens preparation

II.2.1 Hemp Concrete Design

The mixing ratio for the hemp concrete was determined considering a ratio of binder: aggregates: water of 1:0.5:0.93. The mixing procedure was the same for all specimens (sandwich and cylinder). The main difference was the type of the mineral binder included in the composition, and the shape of the mold. First, the hemp shives were placed in a plastic vessel (Figure 1.a). Then, half the amount of water was added and mixed by hand with the hemp shives to hydrate them before adding the cement powder (Figure 1.b). The remaining water was added and the mixture was stirred by hand (Figure 1.c) until all hemp shives were properly coated and adhered to the cement paste (Figure 1.e). Finally, the resulting mixtures were cast in two different types of molds, parallelepiped molds of 40 cm length, 10 cm wide, and 10 cm depth and cylindrical molds of 12 cm diameter and 22 cm height. The casting process consists of compacting the mixture in three successive layers using a wooden stick (Figure 1.f). 48 hours later, the specimens were demolded

(Fig 1.g) and stored in a conditioned room (20°C and 50% RH) for 28 days before the test day. The choice of choosing this type of material as reference specimen is related to the objective of this study to reinforce a vegetable concrete specimens. However, their geometry in the bending reinforced configurations can be a possible application for fascade panels.

The density of the cylindrical and parallelepiped hemp concrete specimens at the hardened state after 28 days is 190 kg/m^3 and 210 kg/m^3 respectively.

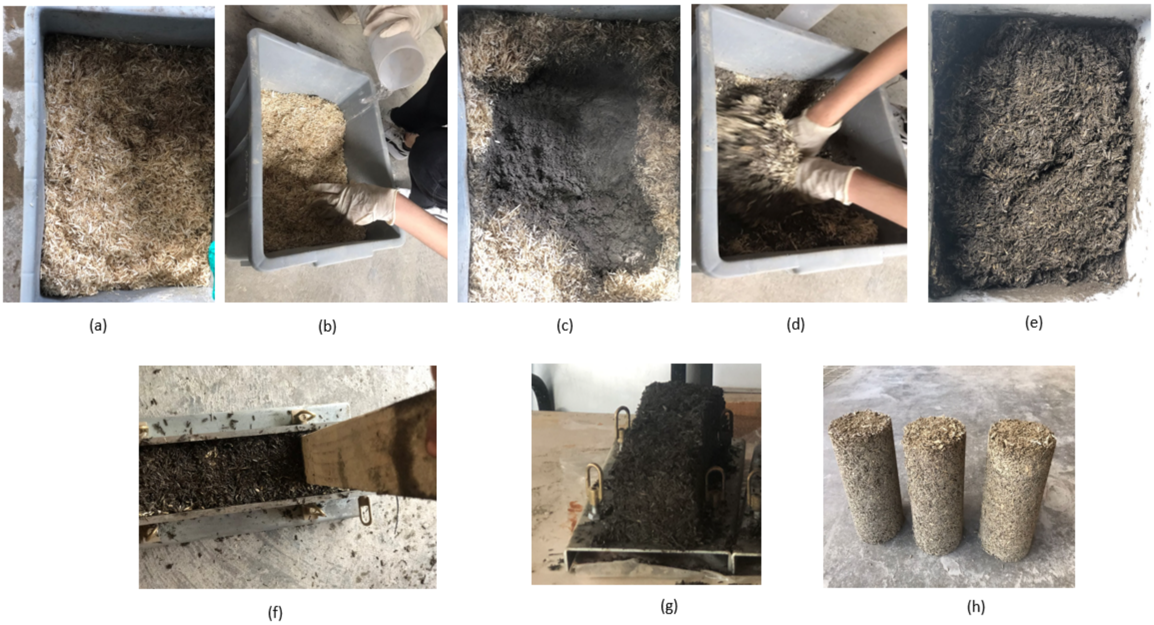

Figure 1 Process of hemp concrete design for bending specimens; (a): dropping of hemp shives, (b): wetting of hemp shives, (c): put on CSA cement, (d): hand mixing of hemp shives with water and cement, (e): status of the resulting mixture, (f): compaction loads on hemp concrete inside the molds, (g): demolded hemp concrete in the case of the parallelepiped molds, (h): demolded hemp concrete in the case of the cylindrical specimens.

II.2.2 Reinforced Hemp Concrete Design

II.2.2.1 Bending Reinforcement

The composite sandwich fabrication process is illustrated in Figure 2. First, a demolding compound was laid into the metal mold to facilitate the demolding later on. A first layer of matrix was positioned at the bottom of the cast mold using a pallet (Fig 2.a), then the pre-cut flax textile (40 cm long and 10 cm wide) was positioned above the matrix layer (Fig 2.b). Manual pressure was exerted on the textile to provide effective penetration of the matrix into the textile yarns. The flax textile was then covered by a second layer of matrix on top of it (Fig 2.c). At this step, the 10 mm thick bottom skin of the FRCM of the composite sandwich was completed. The hemp concrete that was first prepared in Section II.2.1 was added on top of the lower FRCM skin to constitute the core of the sandwich (Fig 2.d). The hemp concrete was inserted in 4 layers, and at the end of each layer, compressive loads were imposed using a wooden stick. Once the sandwich core was appropriately placed in the mold, the constitution of the upper FRCM skin began. A first layer of matrix was added on top of the hemp concrete (Fig 2.e), then a pre-cut flax textile was positioned just above this matrix layer (Fig 2.f). Similarly, manual pressure was employed to provide better penetrability of the cement into the textile yarns. An additional matrix layer was added to overlay the textile and finalize the formation of the 10-mm-thick top skin of the composite sandwich FRCM (Fig 2.g). 48 hours later, the bending reinforced specimens were demolded (Fig 2.h) and placed in a conditioned room (20 °c and 50% RH) for 28 days before testing.

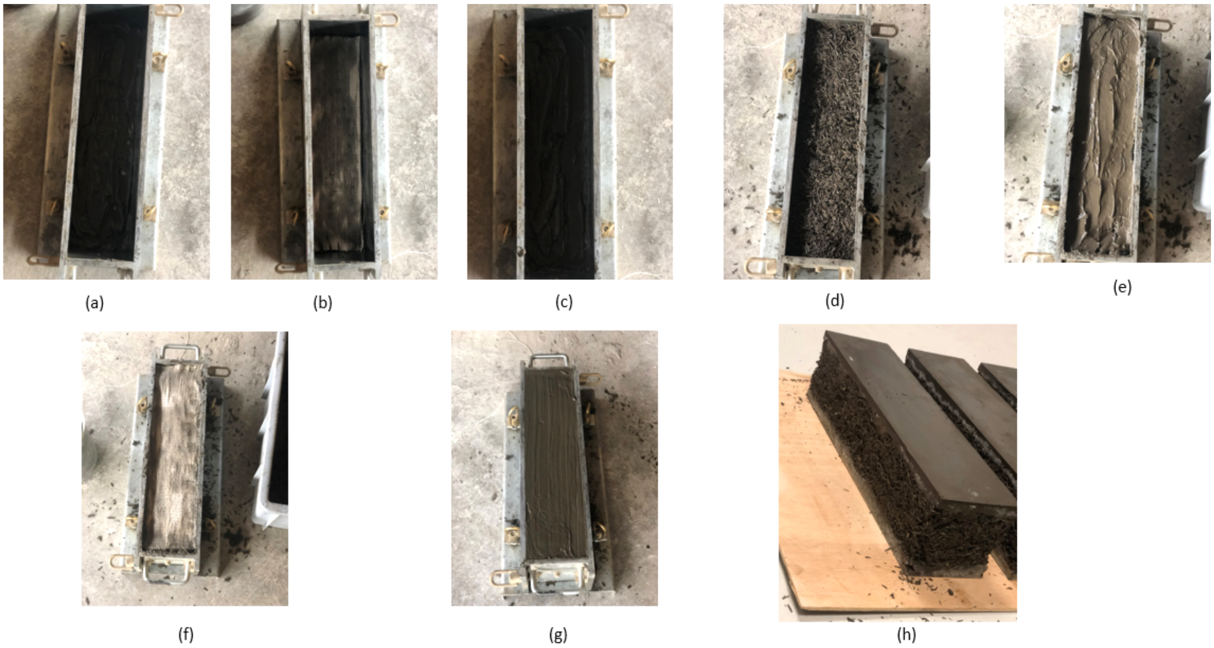

Figure 2 Composite sandwich fabrication process; (a): first layer of cementitious matrix at the bottom of the mold, (b):flax textile placement, (c): second matrix layer to form the lower skin of the sandwich, (d): core of the sandwich by placing hemp concrete, (e): deposit of first matrix layer above the sandwich core, (f): flax textile placement, (g): second matrix layer to finalize the upper FRCM skin, (h): demolded composite sandwich

II.2.2.2 Compressive Reinforcement

After demolding the reference hemp concrete specimens from the cylindrical molds, a first layer of PNC matrix was freshly placed all around the cylinder (Fig 3.a). Then a pre-cut flax textile (44 cm long and 22 cm wide) was manually wrapped over the matrix layer with an overlap length of 10 cm as shown in Fig 3.b). The flax textile was then coated by a second layer of PNC matrix to make the confinement layer (Fig 3.c). The surface was polished with a spatula to create a smooth surface (Fig 3.d). One hour later, the compressive reinforced specimens were placed in a conditioned room at 20°C and 50% relative humidity for 28 days prior to the test day.

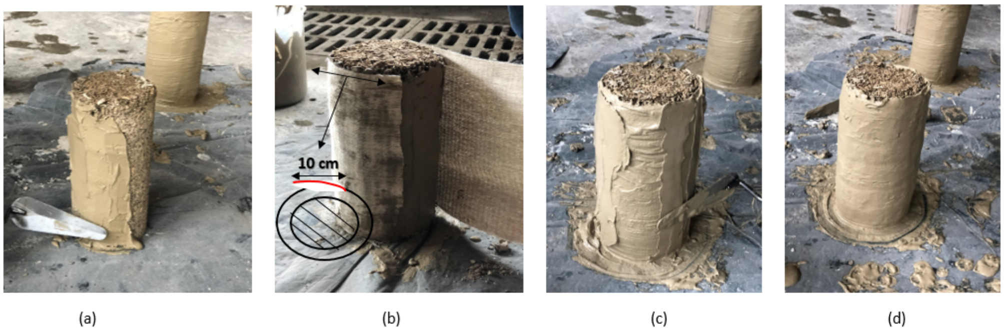

Figure 3 Confined cylinder fabrication process; (a): first layer of cementitious matrix, (b): flax textile wrapping with overlap distance, (c): second layer of cementitious matrix over the placed textile, (d): final state of the confined cylinder

II.3 EXPERIMENTAL CONFIGURATIONS

The experimental configurations in the bending reinforced specimens were adapted to the condition of the upper and lower FRCM skins based on two main parameters: the reinforcement rate and the textile pre-impregnation.

In the case of the bending reinforcement, B.R.1L and B.R.2L refer to the bending reinforced specimens by a composite FRCM comprising one and two textile layers, respectively.

Flax textile at the dry state was designated by NP that denoted non-impregnated textile. Bending reinforced specimens with reference non-impregnated textile were denoted by B.R.NP. However, textile pre-impregnated with CSA matrix, designated as PM. In this impregnation process, pre-cut textiles were immersed in the CSA matrix on both sides. Manual pressure through a polyurethane film was then exerted to provide proper distribution and penetration of the CSA cementitious matrix between the textile yarns. Following this impregnation process, the bending reinforced specimens that contains a flax textile pre-impregnated with CSA matrix were designated as B.R.PM.

On the other side, in the case of compressive reinforced specimens, only one experimental configuration was examined denoted C.R which refers to compressive reinforcement of one non-impregnated flax textile.

In addition to the reinforced specimens, B.REF and C.REF stand for reference specimens in bending and compression, respectively.
Three specimens of each configuration were tested whether by 4 point bending tests or axial compression tests depending on the type of molds that they were casted in. In total, 5 different configurations were casted in parallelepiped molds, resulting in 15 specimens to be tested in 4 point bending tests. On the other part, 2 different configurations were casted in cylindrical molds, resulting in 6 specimens to be tested in compression tests.

III TEST SETUP

III.1 4-point bending tests

The bending tests were performed using a 50 kN Zwick Roelle machine as shown in Figure 4 at a testing rate of 1.5 mm/min. The parallelepiped specimens (reference and bending reinforced specimens) were placed across a span of distance 30 cm. The applied source points were slightly separated between a distance of 10 cm.

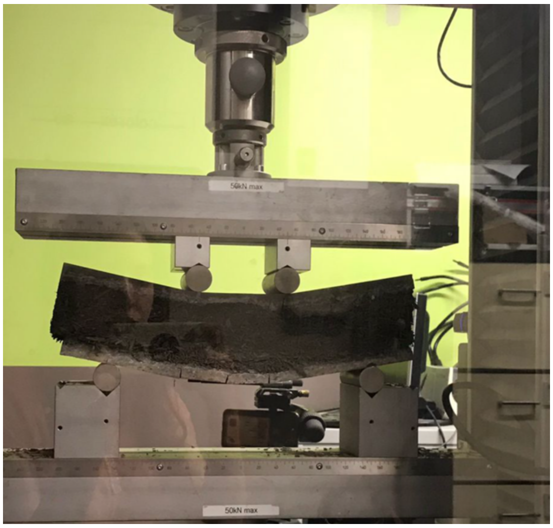

Figure 4 4-point bending test

III.2 Axial compression tests

The compression tests were performed using the same Zwick Roelle machine as shown in Figure 5 but at a testing rate of 3mm/min. The initial distance between the upper and bottom plate of the machine corresponding to the height of the specimen.

Figure 5 axial compression test

IV. RESULTS AND DISCUSSION

IV.1 Mechanical Properties Improvement

IV.1.1 Bending Reinforcement

In this section, the mechanical properties in terms of F_1 and F_{max} of B.R and B.REF specimens are compared. The values of F_1, Fmax, and the mechanical energy are listed in the table below. F_1 denoted the force at the initiation of the first crack at which the force drop, and F_{max} denoted the maximum load capacity endured by the specimens. The mechanical energy W represents the work involved in each specimen that was directly related to the performance of each configuration in cracks propagation. The mechanical energy stored was determined by the area under the curve of Force-mid span deflection up to 40 mm of deflection. In the case of reference bending specimens, no values of F1 was added since there was no retain in strength after cracks as it can be seen in the Figure 4 that the reference hemp concrete showed a continuous failure.

Table 2: Mechanical properties for different configurations of Bending reinforced and bending reference specimens

Parameters		B.R.1L.NP	B.R.1L.PM	B.R.2L.NP	B.R.2L.PM	B.REF
F_1 (kN)	Mean	1.34	1.95	2.05	2.82	-
	CV (%)	15	10	7	3	-
F_{max} (kN)	Mean	2.36	4.33	6.33	8.11	0.046
	CV (%)	17	11	11	5	6
W (MJ)	Mean	54.56	115.86	152.87	188.4	0.18e-6
	CV(%)	6	8	7	6	2

Figure 6 represents the flexural behavior for the reference hemp concrete specimens and for the different configurations of the bending reinforced specimens in case of 1L. In general, it can be observed that the mechanical response of reference hemp concrete showed a very brittle behavior compared to bending reference specimens. A common trend in the flexural behavior for the reinforced specimens was remarked. The flexural behavior for the reinforced specimens was divided in two zones. The first linear zone was mainly affected by the properties of the cementitious matrix (CSA) at the FRCM skins. After the initiation of the first crack at the level of the FRCM layers in the composite sandwich that represents the moment at which F1 was reported. Starting from this crack, a second zone appeared in which both the textile and the cementitious matrix contribute to the mechanical response. During this zone, the two constituents of FRCM work together to reinforce the hemp concrete. The matrix had two functions: it transferred loads to the fabric and provided protection against the external environment. Meanwhile, the fabric carried the loads after the cracks in the matrix have formed. More cracks were observed in the case of B.R.1L.PM than B.R.1L.NP due to the promoted adherence between the mineral impregnated flax textile and the cementitious matrix that led the cement particles to penetrate more easily between the filaments.

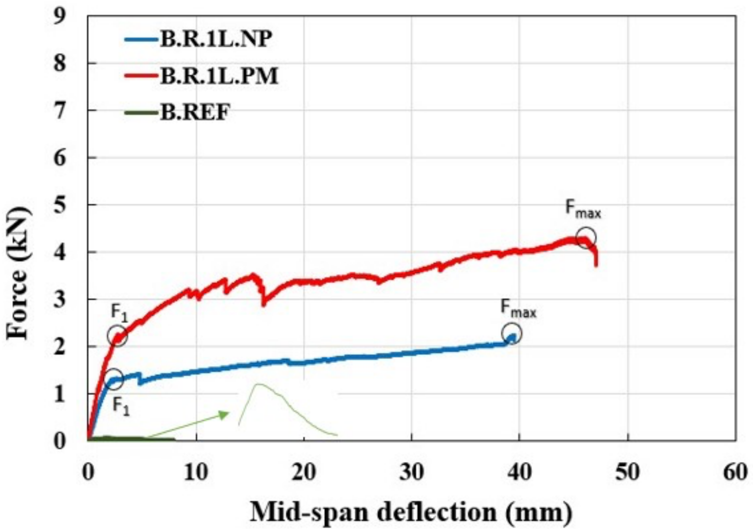

Figure 6 Flexural behavior for reference hemp concrete and for the different configurations of the bending reinforced specimens in the case of 1L.

Figure 7 illustrates the evolution of F_1 and F_{max} with respect to the different configurations studied in bending tests. configurations of the bending reinforced and bending reference specimens.

In general, a tremendous increase in Fmax can be observed between the reference specimens and the bending reinforced specimens. For example, an increase of 5030% and 9313% was obtained when the reinforced configurations B.R.1L. NP and B.R.1L.PM were used, respectively. This significant improvement is due to two main reasons: first, the very low mechanical strength of the reference hemp concrete and second, the performance of the FRCM composite structures to reinforce lightweight structures.

The addition of a second textile layer resulted in an overall improvement in F1 and Fmax due to the additional strength that the next flax textile provides to the configuration. For example, a 53% and 45% gain in F1 was observed when the textile layer was doubled from 1L to 2L for the B.R. NP and B.R.PM configurations, respectively. Similarly, an increase of 168% and 87% in terms of Fmax was obtained when the B.R. NP and B.R.PM configurations were varied from 1L to 2L, respectively.

On the other hand, mineral impregnation resulted in a general improvement of F1 and Fmax. Thus, the increase in F1 when the textile state was changed from NP to PM was 45% and 38% for the 1L and 2L configurations, respectively. This improvement was attributed to the increased adhesion strength between the cementitious matrix and the inner flax yarns, allowing the latter to further support the mechanical response.

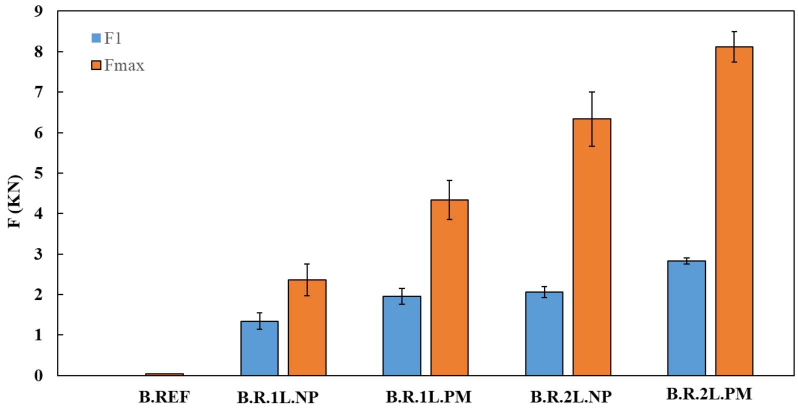

Figure 7 Evolution of F_1 and F_{max} for the bending reference and bending reinforced specimens depending on the reinforcement ratio and the pre-impregnation technique.

IV.1.2 Compressive Reinforcement

The values of the mechanical strength σ_{max}, and the rigidity E for the different configurations are listed in the table below.

Table 3: Maximum strength σ_{max} of the compressive reinforced and compressive reference specimens.

Parameters		C.REF	C.R
σ_{max} (MPa)	Mean	0.26	0.93
	CV (%)	12	12
E (MPa)	Mean	4.73	29.83
	CV (%)	7	10

Figure 8 shows the maximum strength for the compressive reinforced specimens compared to the reference specimens. A gain of 257 % can be achieved for the C.R specimens compared to C.REF. This huge gain was mainly due the low compressive strength of the reference specimens and the capacity of FRCM composite structure to withstand high uniaxial compression loads.

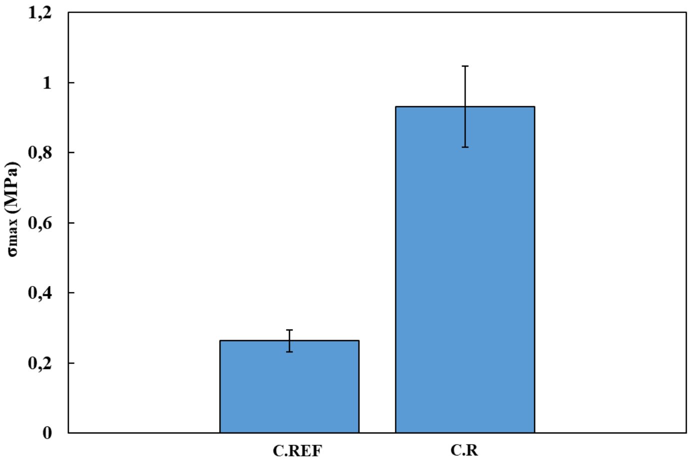

Figure 8 The mechanical strength σmax for the compressive reference and compressive reinforced specimens.

V. CONCLUSION

Based on the experimental results obtained, the following conclusions can be derived:

1. In the flexural behavior, reference hemp concrete specimens exhibit a very low mechanical resistance and a brittle behavior compared to bending reinforced specimens.
2. A considerable improvement in the mechanical properties of the reference hemp concrete was achieved by the bending and compressive reinforced techniques applied due to the effectiveness of FRCM in strengthening lightweight structures.
3. The mineral pre-impregnation improved the mechanical properties of the bending reinforced specimens in terms of strength due to the improved bonding between the flax yarns and the CSA matrix, which enabled an effective contribution of the fabric to the mechanical response.

VI. REFERENCES

[1] Ministère du développement durable et de l'énergie, L'environnement en France, 2014 http://www.statistiques.developpement-durable.gouv.fr/%20fileadmin/documents/Produits_editoriaux/Publications/References/2014/%20references-ree-2014.pdf

[2] Jami, T., Karade, S.R. and Singh, L.P., 2019. A review of the properties of hemp concrete for green building applications. Journal of Cleaner Production, 239, p.117852. https://doi.org/10.1016/j.jclepro.2019.117852

[3] Ratsimbazafy, H., Laborel-Préneron, A., Magniont, C. and Evon, P., 2021. A Review of the Multi-Physical Characteristics of Plant Aggregates and Their Effects on the Properties of Plant-Based Concrete. Recent Progress in Materials, 3(2), pp.69-p.

[4] Elfordy, S., Lucas, F., Tancret, F., Scudeller, Y. and Goudet, L., 2008. Mechanical and thermal properties of lime and hemp concrete ("hempcrete") manufactured by a projection process. Construction and Building Materials, 22(10), pp.2116-2123. https://doi.org/10.1016/j.conbuildmat.2007.07.016

[5] Hirst, E., Walker, P., Paine, K. and Yates, T., 2010, June. Characterisation of low density hemp-lime composite building materials under compression loading. In Second international conference on sustainable construction materials and technologies (pp. 28-30).

[6] Walker, R., Pavia, S. and Mitchell, R., 2014. Mechanical properties and durability of hemp-lime concretes. Construction and Building Materials, 61, pp.340-348. https://doi.org/10.1016/j.conbuildmat.2014.02.065

[7] Sellami, A., Merzoud, M. and Amziane, S., 2013. Improvement of mechanical properties of green concrete by treatment of the vegetals fibers. Construction and Building Materials, 47, pp.1117-1124. https://doi.org/10.1016/j.conbuildmat.2013.05.073

[8] Karade, S.R., 2010. Cement-bonded composites from lignocellulosic wastes. Construction and building materials, 24(8), pp.1323-1330. https://doi.org/10.1016/j.conbuildmat.2010.02.003

[9] Wei, Y.M., Zhou, Y.G. and Tomita, B., 2000. Study of hydration behavior of wood cement-based composite II: effect of chemical additives on the hydration characteristics and strengths of wood-cement composites. Journal of wood science, 46(6), pp.444-451. https://doi.org/10.1007/BF00765802

[10] Amziane, S., Nozahic, V. and Sonebi, M., 2015. Design of mechanically enhanced concrete using hemp shiv. Academic Journal of Civil Engineering, 33(2), pp.422-426. https://doi.org/10.26168/icbbm2015.65

[11] Nanni, A., 2012. A new tool for concrete and masonry repair. *Concr. Int*, *34*(4), pp.43-49.

[12] Dalalbashi, A., Ghiassi, B. and Oliveira, D.V., 2021. A multi-level investigation on the mechanical response of TRM-strengthened masonry. *Materials and Structures*, *54*(6), p.224.

[13] Hallonet, A., Michel, L. and Ferrier, E., 2016. Investigation of the bond behavior of flax FRP strengthened RC structures through double lap shear testing. *Composites Part B: Engineering*, *100*, pp.247-256.
https://doi.org/10.1016/j.compositesb.2016.06.049