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Lime-based plasters reinforced with hemp meshes for retrofitting masonry structures

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Abstract

The recent earthquakes in the Mediterranean area provoked serious damages and collapses to the built-up, including masonry buildings that represent the highest percentage of existing structures. The protection of the historical heritage to prevent economic and human losses is always accompanied by the compelling need of preserving the environment due to the increasing attention to the sustainability issue. In this framework, retrofit solutions already widespread and effective in the Seismic Engineering field can also be improved from an environmental point of view. In past years, one of the techniques most applied to masonry structures is the Fiber Reinforced Cementitious Matrix (FRCM), that is usually made of artificial fibres, such as steel, carbon, and glass, immersed into a matrix used to fix the reinforcing system to the structural support. The sustainability of this reinforcement kind can be improved by replacing artificial fibres with natural ones, such as hemp, that claims good mechanical properties and is carbon negative. The research aims at experimenting a retrofitting system, called Hemp-FRCM, that is made of a hemp mesh drowned in a lime matrix. The hemp fibres are preliminary subjected to tensile tests. Then, the Hemp-FRCM system is applied to a brick masonry wall tested under compressive loads. Finally, the adhesion capacity of the system to a Neapolitan yellow tuff support is evaluated by performing delamination tests. The experimental campaign shows promising results on the use of hemp meshes instead of artificial systems for the structural retrofit of existing masonry buildings.

Keywords: Delamination tests; FRCM; Hemp mesh; Masonry buildings; Natural fibres; Sustainable materials

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1. Introduction

Recognizing the significant environmental impact of constructions highlights the crucial need to encourage both building efficiency and the adoption of sustainable, recyclable materials as measures against global warming and climate change. Enhancing the sustainability of construction materials can involve actions such as modifying production processes to lower carbon dioxide emissions or substituting certain raw materials with eco-friendly alternatives. Natural fibres, that represent a renewable resource with both low environmental impact and cost as stated by Pickering et al. (2016), also offer structural advantages due to their good mechanical characteristics, as documented in studies on various plant-based fibres like jute in Zakaria et al. (2016), flax in De Rosa et al. (2012) and hemp. Specifically, Prasad and Sain (2016) showed that hemp fibres are an outstanding solution due to both their promising mechanical properties and environmental benefits. Primarily, hemp stands out as a carbon-negative plant. One hectare of hemp absorbs CO_2 four times more than a forest of the same area as reported in Piot at al. (2017). Mercedes et al. (2018) explored incorporating hemp fibres, either with a random distribution or under form of mesh, into a lime matrix, demonstrating their positive impact on enhancing the behaviour of the base material. If compared to other natural fibres, such as flax, sisal and cotton, in the manufacturing of Fiber Reinforced Cementitious Matrices (FRCM), hemp fibres allow to reach higher values of tensile strength. Asprone et al. (2011) showed that hemp grids can improve the flexural behaviour of a pozzolan-based mortar by increasing both the strength and the ductility of the base material. Finally, plastering a yellow tuff wall with a mortar reinforced with hemp meshes can lead to an increase of the shear strength by a factor of around 2-3 as demonstrated in Menna et al. (2015). The current research aims to assess the behavior of a Hemp-FRCM retrofitting system, manufactured by drowning a hemp mesh in a lime-based matrix. The first part of the research concerned the investigation under compression test of a masonry wall made of solid bricks reinforced with a 20x20 mm hemp mesh and the comparison of the results with those obtained for the same wall without the reinforcement. The hemp braids used to manufacture the mesh were preliminary subjected to tensile tests. The second part of the investigation regarded the tensile test of a hemp mesh with spacing of 30x30 mm and the evaluation of the adhesion capacity of the Hemp-FRCM system to the support made of Neapolitan yellow tuff blocks. The results were compared to the ones related to a FRCM system made of glass fibres to show the performance of the natural system.

2. Phase I: compressive tests on unreinforced and reinforced walls

2.1. Materials and manufacturing of specimens

The research was conducted by comparing the performances of a solid brick wall simply plastered on both sides and a solid brick wall reinforced on both sides with the proposed hemp mesh drowned in a plaster layer.

The support walls have dimensions of 50x50 cm with a thickness of 12 cm and are made of 12x25x5.5 cm solid bricks having a compressive strength of 38.15 MPa. The bricks were laid with a shrinkage controlled cementitious mortar having a compressive strength of 18.2 MPa. The product used for plastering the walls is a pre-mixed lime-based mortar classified as M5 according to the EN 998-1:2016 standard.

The fabrication of specimens for reinforced wall initially involved the fabrication of the hemp mesh by using hemp braids having a diameter of 2 mm. The formation of the 20x20 mm mesh was obtained by weaving the hemp braids on a register and bonding the joints among orthogonal braids with a vinyl acetate adhesive. The support walls were constructed by placing the solid bricks with staggered joints in a wooden formwork. After 28 days of curing of the mortar joints, the wall was plastered on both sides with two 1.5 cm thick layers of lime-based mortar where the hemp mesh was embedded. The connection between the mesh and the wall was ensured by means of four mechanical anchors at the corners of the wall connecting the hemp meshes on the two sides of the wall. The mechanical anchors are made of plastic plug, stainless steel threaded rod having diameter of 8 mm and nut (Fig. 1b.). Once the specimens were completed, the top section was regularized with a hi-flow mortar to obtain a perfectly smooth surface in contact with the testing machine. The manufacturing of the unreinforced specimen followed the same procedure seen for the base structure of the reinforced sample, as illustrated in Fig. 1a.

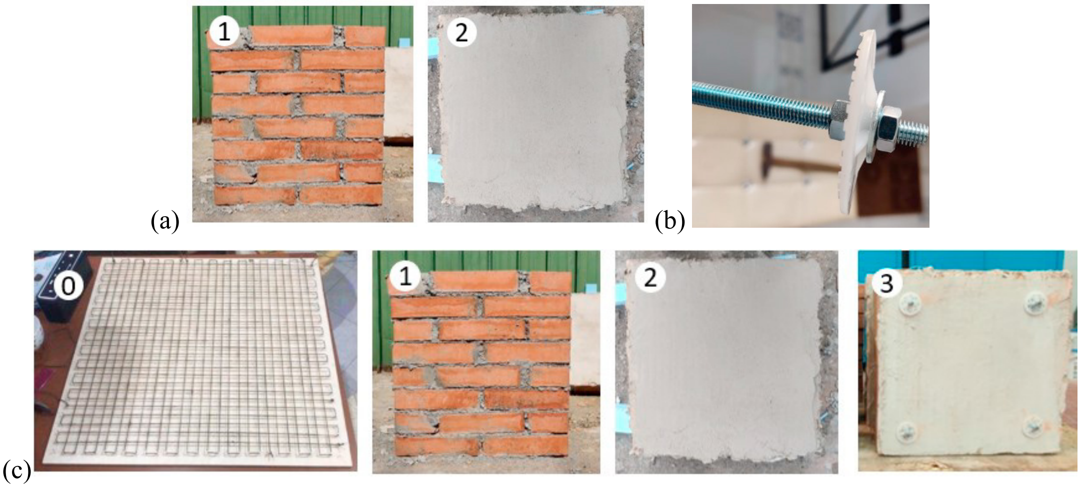

Fig. 1. Manufacturing of unreinforced wall (a), mechanical anchors used for the reinforced wall (b) and manufacturing of reinforced wall samples (c).

2.2. Preliminary tensile tests on hemp braids

The hemp braids used to create the hemp mesh were subjected to tensile tests before the execution of the mechanical tests on the wall samples. The uniaxial tensile tests were performed on three specimens of hemp braids having diameter of 2 mm and overall length of 70 cm, which was based on end anchor lengths of 10 cm and a test reference length of 50 cm. The tests were carried out using a universal displacement-controlled machine that returned the force-displacement diagram of the braids. The hemp braids showed an average value of tensile strength of around 60 MPa, as shown in Fig. 2.

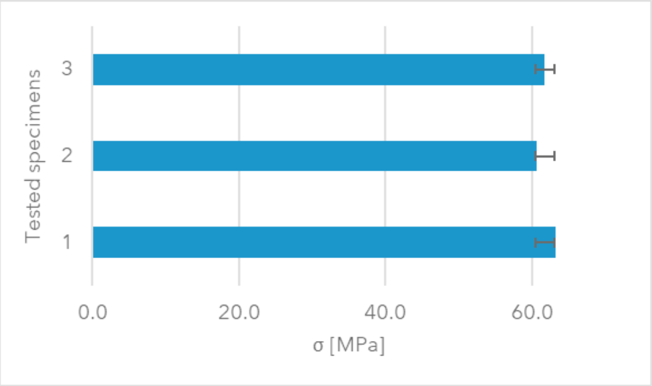

Fig. 2. Tensile strengths of hemp braids with diameter of 2 mm.

2.3. Compressive tests

The samples were subjected to a mechanical compression test using a universal displacement-controlled machine with a load capacity of 1000 kN. Prior the execution of the tests, three displacement transducers were placed on each side of the specimens to monitor the vertical displacements and another one was used to monitor the horizontal displacements (Fig. 3).

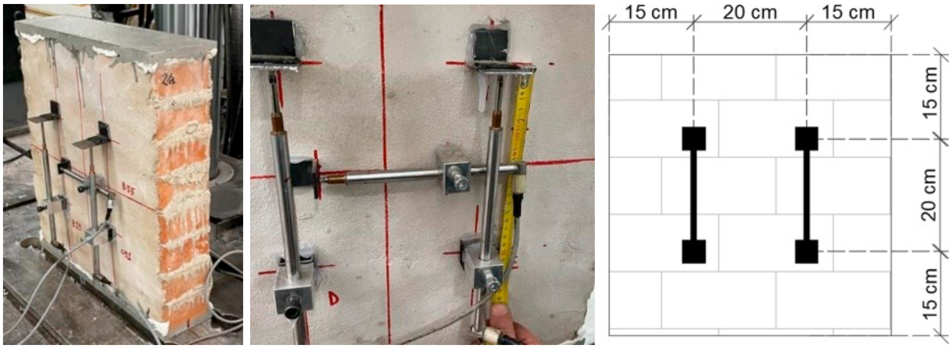

Fig. 3. Compressive test on the unreinforced masonry wall and position of the transducers.

The results of the compression test are shown in Fig. 4 in terms of force-displacement (F-δ) curve, where the displacements were computed as the average value of the values recorded by the four vertical transducers placed on each specimen. To evaluate the different performances of the unreinforced (Control_01) and reinforced (Reinf_01) specimens, the results obtained from the tests in terms of ultimate force (F_u) and the corresponding average displacement (δ_u) are summarized in Table 1.

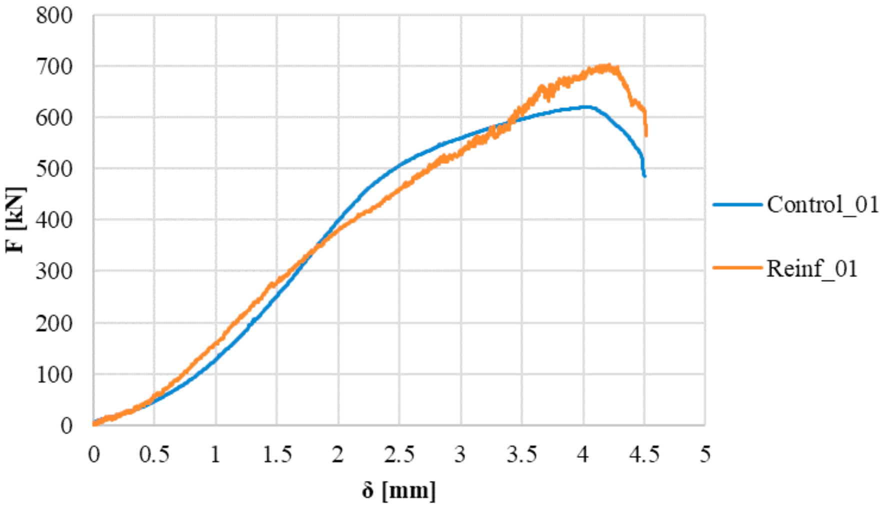

Fig. 4. Force-displacement curves of unreinforced and reinforced specimens.

Table 1. Results of compression test on unreinforced and reinforced solid brick masonry walls.

ID	F_u [kN]	δ_u [cm]
Control_01	619.4	4.03
Reinf_01	703.8	4.21
Δ [%]	13.6%	4.5%

It was found that the hemp fibres mesh gives an increase of ultimate strength and displacement approximately 14% and 4.5% greater than those of the unreinforced wall. The most interesting result of the experiment concerns the collapse modes of the two specimens. In fact, at the end of the test, specimen Control_01 showed large vertical cracks in the bricks and the plaster layers covering the wall were completely ejected. On the other hand, test sample Reinf_01, thanks to the presence of the hemp mesh and the mechanical anchors, did not show any significant lesions in the bricks, but only the onset of a capillary cracking pattern. Furthermore, the hemp mesh and the anchors avoided the expulsion of the plaster (Fig. 5). Therefore, the proposed system manifested an effective confinement action of the wall specimen, with a good increase in strength compared to the system without the reinforcement mesh.

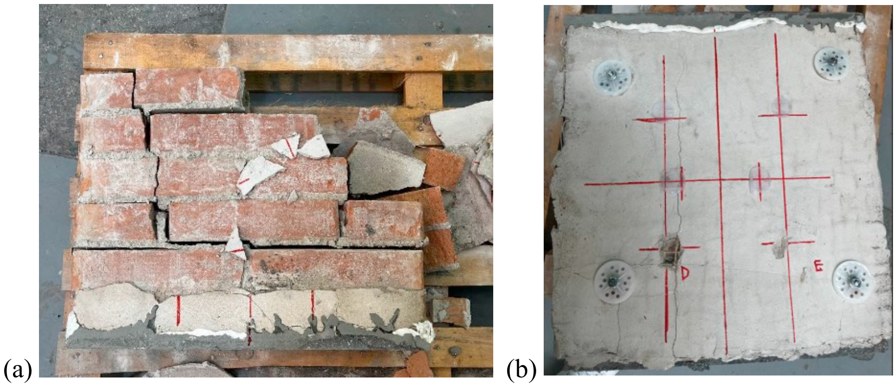

Fig. 5. Unreinforced (a) and reinforced (b) masonry samples after compression tests.

3. Phase II: tensile and delamination tests on hemp mesh

3.1. Tensile tests

The tensile tests on hemp meshes were conducted according to the indications of the Italian Guidelines for the identification, qualification, and acceptance control of FRCM systems for the structural consolidation of existing buildings (2018). The tests were performed, without considering the presence of the inorganic matrix, on specimens extracted from a 30x30 mm hemp mesh with a number of braids, having diameter of 3 mm, equal to 1, 2 and 3. Fig. 6 shows the different types of samples subjected to tensile tests. Three specimens were tested for each hemp mesh type. The tests were performed with a 50 kN displacement-controlled machine with a speed of 0.5 mm/min (Fig. 7).

Fig. 6. Specimens of hemp meshes subjected to tensile tests.

Fig. 7. Tensile tests on hemp meshes.

During the test, the load and displacement values were recorded, and the ultimate strength of the mesh was computed according to the following formula:

$$\sigma_{uf} = \frac{F_u}{n \cdot A_{fv}}$$

where n is the number of braids and A_{fv} is the resistant area of the single braid. The results of the tensile tests are depicted in the histogram of Fig. 8, where the red line represents the average strength which is about 58 MPa.

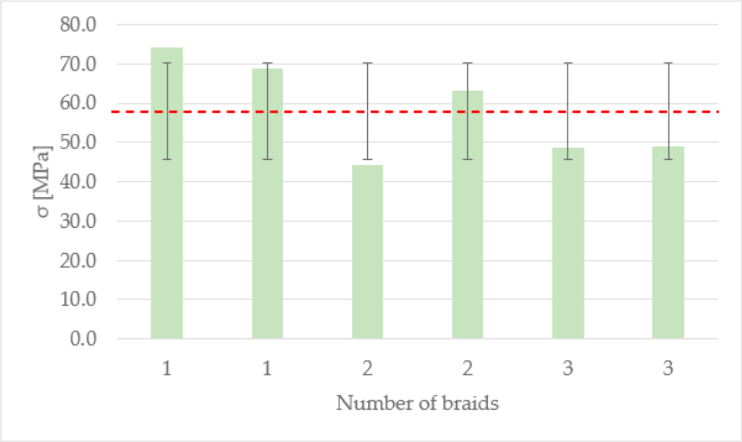

Fig. 8. Tensile strengths of hemp meshes.

3.2. Delamination tests

The delamination test is intended to quantify the maximum force that can be transferred from the hemp mesh to the substrate, as well as to identify the crisis mechanism occurring because of the substrate-reinforcement interaction. The tests were conducted on both the FRCM system made of the 30x30 mm hemp mesh (H-FRCM) and the one produced with a 20x20 mm glass mesh (G-FRCM), a common system already present on the building market for comparison purpose. In both cases, samples of tuff masonry were manufactured to apply the FRCM system made of a single mesh embedded in two layers of lime-based mortar with compressive strength ≥ 15 MPa (M15) and total thickness of 15 mm. The FRCM samples, having length of 20 cm and width of 6 cm, were made of three braids for the H-FRCM system and four braids for the G-FRCM one (Fig. 9). The specimens were manufactured according to the indications of the Italian Guidelines for FRCM (2018) and the test was performed by applying a shear force to the FRCM system parallel to the mesh plane using a steel plate.

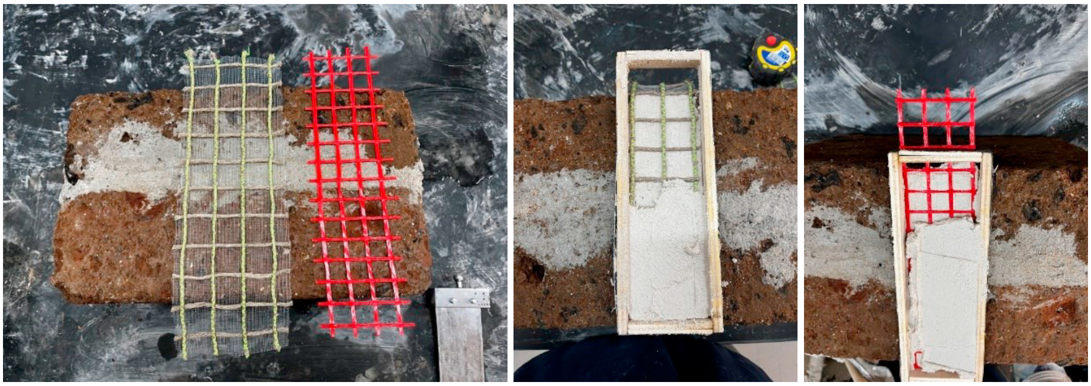

Fig. 9. Preparation of FRCM systems for the delamination tests.

At the end of the test, it was possible to identify the crisis mechanism and to derive the conventional limit stress ($\sigma_{\text{lim, conv}}$) as the ratio of the detachment force (F) to the cross-sectional area of the mesh without considering the inorganic matrix (A_f). Figure 10 shows the collapse mechanisms emerged from the test. For the H-FRCM specimen it was recorded a detachment at the matrix-mesh interface, while for the G-FRCM specimen it was observed a detachment with cohesive failure of the substrate. The different type of collapse is probably due to an ineffective adhesion between the hemp mesh and the matrix that could be improved by using either a different type of matrix or a coating for the natural fibres.

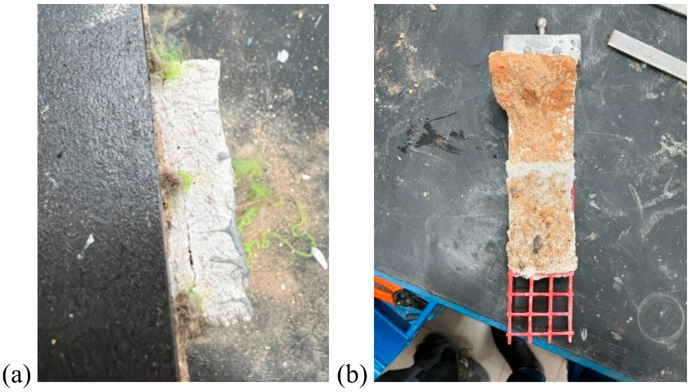

Fig. 10. Crisis mechanisms of the H-FRCM (a) and G-FRCM (b) specimens.

The maximum force and the conventional limit stress are graphically illustrated in Fig. 11. The results showed that the performances of the hemp fibres system are lower than those of the glass fibres specimen. Therefore, further experiments should be carried out to obtain the optimal geometrical and physical configuration of the H-FRCM system to improve its adhesion to the substrate.

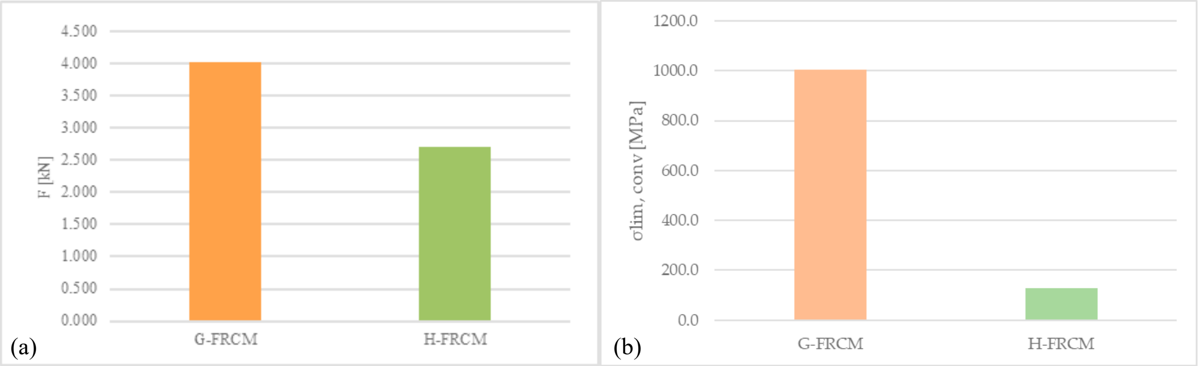

Fig. 11. Maximum force (a) and conventional limit stress (b) of the H-FRCM and G-FRCM systems.

4. Conclusions

The research investigated lime-based plasters reinforced with hemp meshes for retrofitting masonry structures. A first part of the research saw tensile tests on hemp braids and compressive tests on both a plastered brick wall and a wall reinforced with hemp mesh. The hemp reinforcement allowed to increase both ultimate compressive load and ultimate displacement of 14% and 4.5%, respectively, compared to the corresponding values of the unreinforced masonry sample. The reinforcement was found to be particularly effective with regards to the collapse mode of the walls. Following the compression test, in fact, the unreinforced wall showed the almost total expulsion of the plaster and vertical cracks in the bricks. On the contrary, the hemp-reinforced wall showed a capillary cracking framework without both relevant lesions in the bricks and expulsion of the plaster. The second part of the research involved the tensile tests on hemp meshes and delamination tests on a Hemp-FRCM system. The tensile tests showed an average ultimate strength of around 60 MPa, which is in line with the results obtained for hemp braids in the first part of the research. Preliminary delamination tests were carried out on FRCM samples with hemp mesh and compared to a system with a glass fibres mesh. The results showed different crisis mechanisms, namely the matrix-mesh interface detachment for the H-FRCM system and the detachment with cohesive failure of the substrate for the G-FRCM system. The preliminary results showed that the limit conventional stress of the H-FRCM is around 87% lower than the glass fiber FRCM one. Therefore, the future research development is to experiment new system configurations and appropriate type of matrix to increase the adhesion stress between the H-FRCM system and the masonry support.

References

Asprone, D., Durante, M., Prota, A., Manfredi, G., 2011. Potential of structural pozzolanic matrix-hemp fiber grid composites. Construction and Building Materials 25, 2867-2874.

De Rosa, I. M., Kenny, J. M., Puglia, D., Santulli, C., Sarasini, F., 2012. Tensile behavior of new zealand flax (phormium tenax) fibers. J. Reinf. Plast. Compos. 29, 3450–3454.

Higher Council for Public Works, Central Technical Service, Italian Guidelines for the identification, qualification, and acceptance control of FRCM systems for the structural consolidation of existing buildings, December 2018.

Menna, C., Asprone, D., Durante, M., Zinno, A., Balsamo, A., Prota, A., 2015. Structural behaviour of masonry panels strengthened with an innovative hemp fibre composite grid. Constr. Build. Mater. 100, 111–121.

Mercedes, L., Lluis, G., Bernat-Maso, E., 2018. Mechanical performance of vegetal fabric reinforced cementitious matrix (FRCM). Construction and Building Materials 175, 161-163.

Pickering, K. L., Efendy, M. G. A., Le, T. M., 2016. A review of recent developments in natural fibre composites and their mechanical performance. Compos. Part A: Appl. Sci. Manuf. 83, 98–112.

Piot, A., Béjat, T., Jay, A., Bessette, L., Wurtz, E., Barnes-Davin, L., 2017. Study of a hempcrete wall exposed to outdoor climate: Effects of the coating. Constr. Build. Mater. 139, 540–550.

Prasad, B. M., Sain, M. M., 2016. Mechanical properties of thermally treated hemp fibers in inert atmosphere for potential composite reinforcement. Mater. Res. Innov. 7, 231–238.

Zakaria, M., Ahmed, M., Hoque, M. M., Islam, S., 2016. Scope of using jute fiber for the reinforcement of concrete material. Text. Cloth. Sustain. 2, 1-10.