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Jute Fiber Composite Mortars: Sustainable Solutions for Thermo-Mechanical Retrofitting in Construction

Arnas Majumder[a*], Flavio Stochino[b], Andrea Frattolillo[b], Monica Valdes[b], Enzo Martinelli[c]

[a] *Department of Electrical and Electronic Engineering, University of Cagliari, 09123 Cagliari, Italy*
[b] *Department of Civil Environmental Engineering and Architecture, University of Cagliari, via Marengo 2, 09123 Cagliari, Italy*
[c] *Department of Civil Engineering, University of Salerno, via Giovanni Paolo II n.132, 84084, Fisciano, (SA), Italy*

Abstract

Usually, man-made fibers are used in the construction and building sector for retrofitting or reinforcing purposes. However, these fibers are costly, non-biodegradable, non-recyclable, and contribute significantly to a higher carbon footprint, unlike natural fibers. Instead, jute fiber, being a bio-based natural alternative, ranks as the second most produced natural fiber and is recognized for its commendable thermal and mechanical properties.

This paper explores the dual applicability of jute fiber composite mortar for thermo-mechanical upgrading and retrofitting. The research started at the fiber and thread level, involving the assessment of the physical characteristics and mechanical behaviors of raw jute fibers. Subsequently, this data was utilized to create jute fiber composite mortars, incorporating two distinct products. These composite mortars were formulated using three different jute fiber lengths (30 mm, 10 mm, and 5 mm) and four varying fiber percentages (2.0%, 1.5%, 1.0%, and 0.5%) in relation to the dry mortar masses. In total, 24 combinations of composite mortar samples were prepared. These samples underwent flexural and compression tests, as well as thermal conductivity assessments, enabling the evaluation of their mechanical properties and thermal behaviors.

Keywords: Jute fiber composite mortar, Natural fiber composite mortar, Thermo-mechanical retrofitting, Integrated retrofitting.

* Corresponding author. Tel.: +39 0706755427
E-mail address: arnas.majumder@unica.it

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1. Introduction

Most of the existing masonry buildings around the globe urgently need either structural or thermal or both retrofitting/upgrading to satisfy current regulations. Therefore, integrated (structural and energy) retrofitting/upgrading could be an ideal solution for enhancing the thermo-structural performance of those existing structures or new constructions. A huge portion of the existing buildings are masonry and are susceptible to natural disasters (like earthquakes), on the other hand, they lack energy sustainability, this is since they are built mostly neglecting the seismic and energy protocols like EN 1998-3, (2005) and EN ISO 52016-1, (2017), respectively.

Researchers and scientists are working to achieve an optimum solution in this field. Man-made fibers have proved to be the best for structural retrofitting/upgrading due to their superior mechanical strength and durability. Primarily carbon, glass, and basalt fibers are used in Fiber Reinforced Polymer (FRP) configuration, as highlighted in Suparp et al. (2023), Kalali and Kabir (2012) and Padalu et al. (2019), also in Textile Reinforced Mortar (TRM) configuration, as reported in Babaeidarabad et al. (2014). Sometimes small pieces of glass fibers as in Hong et al. (2020), carbon fibers as in Safiuddin et al., (2022), or steel fibers as in Zampieri et al., (2020) are mixed with mortar to enhance the mechanical performance. Some notable work on the use of Natural FRP (NFRP) and Natural Fiber TRM (NFTRM) can be found In the literature, like the use of NFRP in Codispoti et al. (2015) and Li et al. (2021), hybrid (flex and glass) FRP in Huang et al. (2023), and NFTRM as in Ferrara et al. (2020) and Menna et al. (2015). Notably, in Majumder et al. (2023a) highlight the optimum thermo-acoustic insulation properties of natural fiber, and therefore products derived from natural fibers can be used as building insulation materials. Some interesting research works point to the use and application of natural fibers, such as the use of jute fiber in Majumder et al. (2022a), sisal fiber in Yooprasertchai et al. (2022), Açaí fiber in Da Silva et al. (2023), straw in Azhary et al. (2017), date palm fiber in Benmansour et al. (2014), sawdust fiber in Wei et al. (2023), Furcraea Foetida fiber in Madival et al. (2023) etc.

Whereas as highlighted in Townsend (2019) and Arunavathi et al. (2017) jute is the second most-produced (India, Bangladesh, and China are the main producing countries) natural fiber, and in the last 57 years jute fiber production increased by 1 million tons, and around 6 million households engaged in jute fiber production and the value of jute fiber production is about 1.2 billion dollars. Due to its yellowish color, it is also known as golden fiber. While Majumder et al. (2023b) underlines that the strength and insulating capacity of the jute fiber make it attractive and competitive as a construction material, as well as it is cheap and recyclable. Same as other natural fibers, jute fiber too inherits some disadvantages, Chand and Fahim (2021) have pointed out that when the fiber comes in contact with water the strength of the fiber decreases and increases the moisture absorbability.

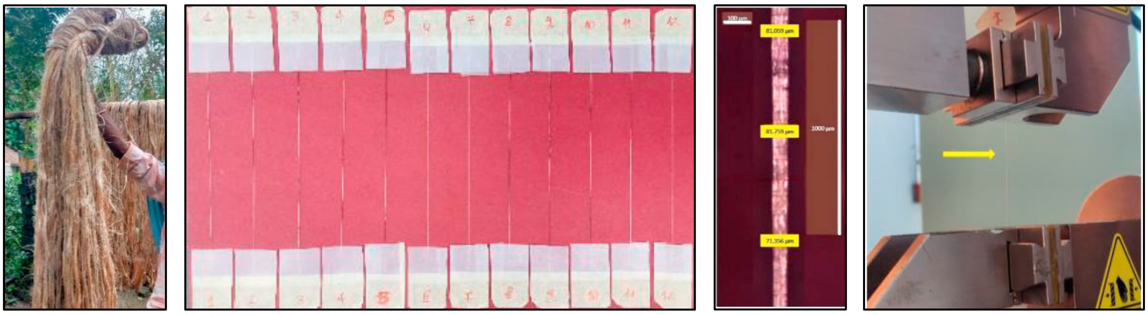
Notably, Islam and Ahmed (2012) have emphasized many positive sides of jute plant cultivation, it improves the fertility of the soil and purifies the air by absorbing CO_2 and emitting O_2. The jute fiber and its derived products are quickly gaining importance in the Construction and Building (C&B) sector. In numerous literature, different innovative applications of jute fiber-derived building materials can be found, like the use and application of jute composite mortars in Majumder et al. (2022a) and Majumder et al. (2024b), jute net in Majumder et al. (2024a), jute-FRP in Ascione et al. (2020), jute epoxy composite in Ferreira et al. (2016), jute fiber crude earth bricks in Saleem et al. (2016), jute fiber burnt bricks in Rashid et al. (2019), concrete retrofitting in Garikapati and Sadeghian (2020), etc. The novelty of this research work is to optimize the composite mortar composition and to identify the best jute fiber percentage (0.5%, 1.0%, 1.5%, and 2.0%) and fiber length (30 mm, 10 mm, and 5mm) combination for integrated retrofitting/upgrading, therefore, to enhance and study the mechanical and thermal properties.

This paper starts with introductory remarks (highlighted in section 1), thereafter the materials used, and methods applied during various phases of the experimental campaign are explained in section 2. Results and observations are discussed in section 3 and followed by the conclusive remarks in section 4.

2. Material and methods

2.1. Raw fiber

Raw jute fiber (Fig. 1.a) used in this experimental campaign is directly collected from West Bengal, India. These fibers are golden in color and notably known as Bangla Tosha – Corchorus olitorius. Intact raw jute fiber length was found to be between 3 m to 4 m. A total of twelve jute fibers were collected randomly from the fiber lot (Fig. 1.b), and the average length and diameter are about 10 cm (with Co.V of 2.64%) and 81.08 µm (with Co.V. of 20.94%), respectively, for details see Majumder et al. (2022b). Fig. 1.c presents the measured diameters (at three points) of the sample JF5, obtained through a Scanning Electron Microscopy (SEM) analysis. The tensile strength of these samples was determined using a digital force gauge (Fig. 1.d), following the ISO 2062 (2009) standard. The gauge has a specification of maximum capacity and displacement rate of 50 N and 0.5 mm/min, respectively. The tensile strength, strain energy, and Young's modulus are found to be about 215.11 MPa (Co.V of 4.4%), 0.77 N.mm (Co.V of 58.85%), and 16.97 GPa (Co.V of 17.89%), respectively. Subsequently, raw fibers were cut into three different (30mm, 10mm, and 5mm) fiber lengths (Fig. 2) to prepare the composite mortars, for details see Majumder et al. (2022b).



(a) *(b)* *(c)* *(d)*

Fig. 1. (a) Raw jute fiber, and (b) Twelve jute fiber samples were used for tensile strength tests, (c) Jute fiber sample JF5: measured diameter, and (d) Jute fiber sample JF7: Tensile strength test.

(a) *(b)* *(c)*

Fig. 2. (a) 30 mm, (b) 10 mm and (c) 5mm chopped jute fibers.

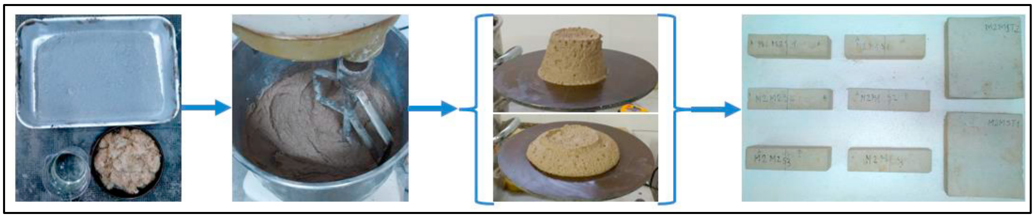
2.2. Mortar and composite mortar preparation

A cement-based premixed mortar (Fig. 3.a) with compressive strength, shear strength, and dry density of 10 MPa, 0.15 MPa, and 1545 kg/m3, respectively, have been chosen. Table 1 presents the various combinations of jute fiber percentages (0.5%, 1.0%, 1.5 %, and 2.0%) and jute fiber lengths (30 mm, 10mm, and 5mm) that have been used for the composite mortar preparation. Table 1 presents the fiber percentages and fiber lengths composition scheme that has been followed for the composite mortar preparation. Notably, the reference mortar and the jute fiber composite mortar grouts (Fig. 3.b) were prepared following the EN 1015-2 (2007) standard, while the reference and composite mortars' workability were determined through the shaking table tests (Fig. 3.c), following the EN 1015-3 (2007) standard. The quantity of water used for each mixture (Table 1) was predetermined based on the water absorption tests, for details see Majumder et al. (2022b). Two types of molds were used to prepare the prismatic samples of dimensions "160 mm x 40 mm x 40 mm" and "160 mm x 140 mm x 40 mm" are used for the mechanical (Fig. 3.d) and thermal conductivity tests (Fig. 3.d), respectively. Sample curing was followed according to EN 1015-11 (2019) standard. After casting, samples were left inside the mold and in a plastic bag for three days. Thereafter samples were taken out from the mold and replaced inside another plastic bag for another five days. Then all samples were taken out from the plastic bag and left in a room (quasi-constant ambient temperature and relative humidity of 25 °C and 65 %, respectively) for natural drying until the twenty-eighth day.

Table 1. Structural Mortar (SM) preparation and Composite SM preparation

		Fiber length categories and water (%) used			
		No fiber	30mm	10mm	5mm
Reference sample	No fiber	P (15.2 %)	-	-	-
Composite samples	0.5%	-	P (16.7 %)	P (17.3 %)	P (17.5 %)
	1.0%	-	P (18.1 %)	P (19.2 %)	P (19.7 %)
	1.5%	-	P (19.3 %)	P (20.6 %)	P (21.5 %)
	2.0%	-	P (20.8 %)	P (22.8 %)	P (23.7 %)

Note: P represents the sample Prepared with the combination (fiber percentage and fiber length), and water (%) used for each combination.

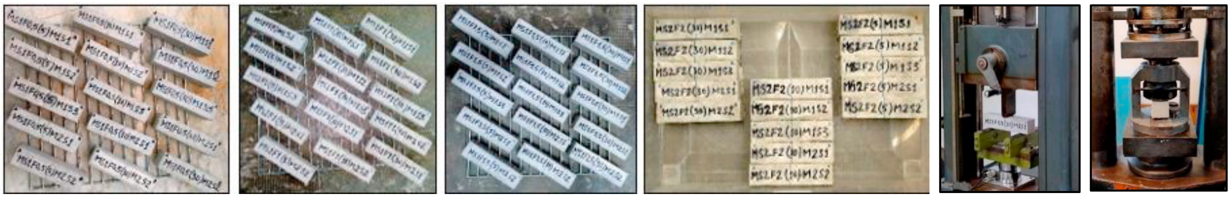


(a) *(b)* *(c)* *(d)*

Fig. 3. (a) Morar, jute fiber, and water, (b) mixture preparation, (c) workability test, and (d) sample natural drying.

2.2.1. Mechanical properties evaluation

Fig. 4.a, Fig. 4.b, Fig. 4.c and Fig. 4.d present composite mortar samples (160 mm × 40 mm × 40mm) with different fiber percentages [(a) 0.5%, (b) 1.0%, (c) 1.5%, and (d) 2.0%] and fiber lengths [5mm, 10mm, and 30mm], respectively. On the 28th day from the casting date, the samples were subjected to flexural (Fig. 4.e) and compression tests (Fig. 4.f), according to the standard EN 1015-11 (2019). A universal displacement-controlled machine with about 5 kN maximum load capacity and sensibility of 0.02 kN, has been used for the flexural tests. Whereas a universal load-controlled machine with a load capacity of 100 kN has been used for the compression tests.



(a) *(b)* *(c)* *(d)* *(e)* *(f)*

Fig. 4. Composite mortar samples with different fiber percentages [(a) 0.5%, (b) 1.0%, (c) 1.5%, and (d) 2.0%] and fiber lengths [5mm, 10mm, and 30mm], (e) Flexural and (f) compression strength tests (Sample MS1F1.5(30)M2S1).

2.2.2. Thermal properties evaluation

On the 28th day from the casting date, the samples (Fig. 5.a) of dimensions 160 mm x 140 mm x 40 mm were put into an oven (Fig. 5.b). The samples were dried at a constant temperature of 50 °C according to EN 12667. This is done to have quasi-precise Thermal Conductivity (TC) values, avoiding the influence of moisture in TC measurements, as reported in Majumder et al. (2021). Whereas, Fig. 5.c presents the TAURUS TCA 300, it is a Heat Flow Meter (HFM) instrument, which has been used to evaluate the insulation properties of the samples with various combinations of different fiber percentages [(a) 0.5%, (b) 1.0%, (c) 1.5%, and (d) 2.0%] and fiber lengths [5mm, 10mm, and 30mm], following ISO 8301 (1991) and EN 1946-3 (1999) standards. The HFM instrument has a measuring chamber and a dedicated computer system. Two measuring plates (hot and cold) are located inside the measuring chamber, and each plate is equipped with a flux sensor. The heat fluxes were measured and the thermal conductivity λ value (W/mK) was calculated by enforcing its definition presented in Eqn. 1.

$$\lambda = \dot{Q}\frac{S}{A(t_H - t_C)} \quad (1)$$

where $\dot{Q}$ is the heat flux in W/m^2, S is the sample thickness in m, t_H is the hot plate temperature in °C; t_C is the cold plate temperature in °C and A is the active zone surface area of the sample under test.

(a) (b) (c)

Fig. 5. Composite mortar samples (160 mm×140mm×40mm) with different fiber % [0.5%, 1.0%, 1.5%, and 2.0%] and fiber lengths [5mm, 10mm, and 30mm], (d) Oven drying and (f) Heat flow meter.

3. Results

3.1. Mechanical and thermal properties

A total of six and twelve samples of reference mortar and composite mortar type of each combination [fiber percentage (0.5%, 1.0%, 1.5%, and 2.0%) and fiber length (30 mm, 10 mm, and 5 mm)] were used for flexural and compressive strength tests, respectively. Fig. 6 presents some of the selective samples after the flexural and compression failures. Fig. 6.a presents the reference sample prepared without any fiber, while Fig. 6.b, Fig. 6.c and Fig. 6.d are the samples with combinations of fiber length & fiber percentage (with respect to the dry mortar mass) of “30 mm & 1%”, “10 mm & 1%” and “5 mm and 1%”, respectively. All the samples without fiber have shown brittle behavior and complete collapse after reaching the ultimate flexural limit. Whereas all the samples with fibers have shown ductile behavior and none of these samples have completely collapsed but rather kept a residual softening behavior with the increase in the maximum deflection. Due to the presence of fiber improvement in the strain energy capacity of the composite mortars has been observed. Fig. 6.e presents the reference sample without fiber after compression failure and a typical hourglass collapse with complete separation of broken pieces has been obtained. Contrary to the case of composite mortars, notably, for all combinations [fiber percentage (0.5%, 1.0%, 1.5%, and 2.0%) and fiber length (30 mm, 10 mm, and 5 mm)] no complete separation of the broken parts is observed when the ultimate compressive strength is reached, but these embodied fibers help in holding the broken parts together, as can be seen in Fig. 6.f. Table 2 presents the mechanical and thermal properties of the reference mortar sample and composite mortar samples with different combinations [fiber percentage (0.5%, 1.0%, 1.5%, and 2.0%) and fiber length (30 mm, 10 mm, and 5 mm)]. Notably due to the application of jute fiber, the flexural and compressive strength capacities of the composite mortar have decreased in all cases, on the other hand, the strain energy capacity has increased, and this improvement is a positive phenomenon and could be helpful to dissipate the extreme load effects, particularly in the case of an earthquake.

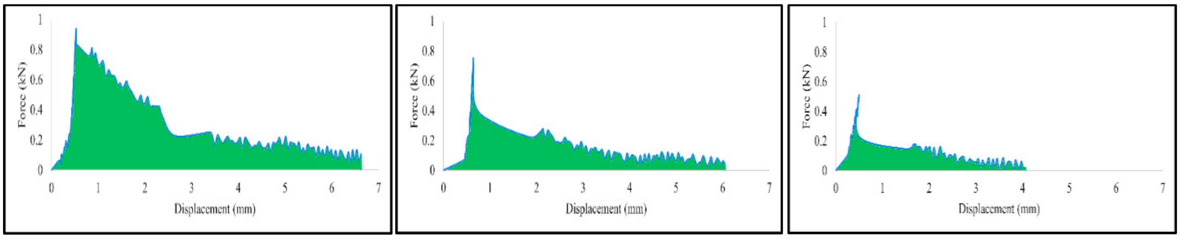
(a) (b) (c) (d) (e) (f)

Fig. 6. Samples after flexural and compression strength tests: (a) Reference samples without fiber and Zoom view of the composite mortar samples (b) MS1F1(30)M1S3, (c) MS1F1(10)M1S1 and (d) MS1F1(5)M1S2, (e) Sample (MS1M2S1) without fiber, and (e) Composite mortar sample MS1F0.5(30)M2S2.

Fig. 7 presents the force-displacement curves of some composite mortar-tested samples. Notably in these figures, the enclosed green part of the curves represents the strain energy (kN.mm). In each fiber category (0.5%, 1.0%, 1.5%, or 2.0%), longer fiber i.e., 30 mm can dissipate more energy when compared with the 10 mm and 5mm one, as shown in Table 2 and Fig. 7.

Table 2. Change thermo-mechanical properties due to the addition of the jute fiber.

Composite mortar Composition categories (Fiber percentage and fiber length)	Flexural strength (MPa)	Compression strength (MPa)	Strain energy capacity (kNmm)	Thermal conductivity (W/mK)
Reference Mortar (without fiber)	7.8	32.25	0.45	0.77
0.5 % and 30 mm	(-) 2.7	(-) 6.1	(+) 0.46	(-) 0.15
0.5 % and 10 mm	(-) 2.0	(-) 5.5	(+) 0.13	(-) 0.26
0.5 % and 5 mm	(-) 1.5	(-) 8.0	(+) 0.23	(-) 0.32
1.0 % and 30 mm	(-) 2.7	(-) 10.4	(+) 0.10	(-) 0.28
1.0 % and 10 mm	(-) 3.7	(-) 14.2	(+) 0.51	(-) 0.28
1.0 % and 5 mm	(-) 3.9	(-) 17.6	(+) 0.32	(-) 0.31
1.5 % and 30 mm	(-) 3.3	(-) 14.5	(+) 1.02	(-) 0.23
1.5 % and 10 mm	(-) 4.1	(-) 18.3	(+) 0.76	(-) 0.29
1.5 % and 5 mm	(-) 4.7	(-) 21.5	(+) 0.24	(-) 0.34
2.0 % and 30 mm	(-) 4.2	(-) 22.1	(+) 2.24	(-) 0.26
2.0 % and 10 mm	(-) 5.1	(-) 23.9	(+) 0.73	(-) 0.31
2.0 % and 5 mm	(-) 5.4	(-) 26.2	(+) 0.22	(-) 0.32



(a) *(b)* *(c)*

Fig. 7. Force-displacement curves of sample (a) MS1F2(30)M1S3, (b) MS1F2(10)M1S1, and (c) MS1F2(5)M1S3.

The insulation capacity (with lower TC value) of the jute fiber composite mortar has increased, for each combination [fiber percentage (0.5%, 1.0%, 1.5%, and 2.0%) and fiber length (30 mm, 10 mm, and 5 mm)]. The samples with higher fiber % (with respect to the dry mortar mass) and smaller fiber have lower TC values and, therefore better insulation properties (Table 2).

During this experimental campaign, the effect of moisture on the TC value has been evaluated. Some selected samples were subjected to TC measurements during the natural drying period (on 9th, 15th, 22nd, and 28th of the drying day) and after the forced oven drying on the 37th day from the day of casting. Fig. 8 shows the decrease in TC values with the gradual sample drying days, and it is true for all other samples observed.

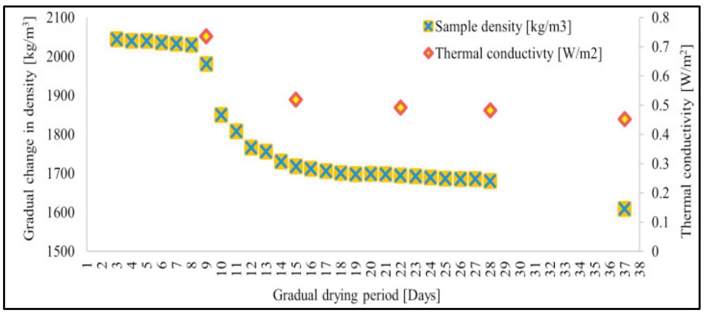


Fig. 8. Effect of water content on thermal conductivity. MS1F2(5)T1.

4. Conclusion

This study investigates the mechanical and thermal properties of jute fiber composite mortars with different compositions [fiber percentage (0.5%, 1.0%, 1.5%, and 2.0%) and fiber length (30 mm, 10 mm, and 5 mm)]. Additionally, this paper explores the dual applicability of jute fiber composite mortar for thermo-mechanical upgrading and retrofitting. It has been observed that (i) The application of jute fiber entails the modification in mechanical properties. Notably, both flexural and compression strengths of the composite mortar samples have decreased, while the strain energy capacity has increased significantly. (ii) The reduction in flexural and compression strength is linearly proportional to the increase in fiber percentages from 0.5% to 2.0% with respect to the dry mortar mass. (iii) The highest reduction in flexural and compression strengths of 5.4 MPa and 24.2 MPa, respectively have been observed for the composite mortar sample with 2.0% fiber (5 mm) with respect to the dry mortar mass, when compared with reference mortar. (iv) Samples with longer fiber i.e., with 30 mm have shown the highest increase in strain energy capacity. Therefore, they can dissipate more energy (during seismic effect) when compared with the 10 mm and 5mm fiber lengths. (v) Thermal conductivity value decreases with the increase of fiber percentage in the composite mortar samples. Notably, the samples with smaller fiber length (5 mm) have shown better insulation capacity and this reduction was more than 0.30 W/mK when compared with reference mortar. (vi) The moisture content influences the thermal conductivity value i.e., the insulation capacity of the mortar samples.

The knowledge gained during this research work has been used for masonry wall retrofitting/upgrading. The optimum combination of fiber length and fiber percentage (with respect to the mortar mass) has been selected for the integrated retrofitting/upgrading purpose.

Acknowledgment

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