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Enhancing Sustainability in Construction: Water Effect on Jute Fiber Composite Mortar

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Abstract

The use and application of natural fiber in the Construction and Building sector is gaining momentum due to its various advantages over synthetic fibers, mainly in terms of sustainability, recyclability, and biodegradability.

In this paper, two aspects of the jute fiber composite mortar have been discussed. Firstly, the effect of water on the mechanical performance of the jute fiber composite mortar samples has been presented here. Secondly, the Digital Image Correlation (DIC) method has been used to analyze and determine the crack openings (mm), in the deformed specimens that occurred during the flexural tests.

Notably, for 0.5% (fiber lengths: 30 mm, 10 mm, 5 mm) and 1.0% (fiber length: 30mm) fiber (with respect to the dry mortar mass) composite mortar samples prepared with the same water amount, exactly the same used for the mortar (without fiber). The reduction in flexural (−1.47 to −2.79 MPa) and compression strengths (−5.4 to −14.01 MPa) have been observed when compared with similar combinations (fiber % and fiber lengths) prepared with different amounts of water for every mixture. Whereas, when these composite mortars are compared with samples prepared with the same average water, increment in flexural strengths (0.24 to 1.45 MPa), while changes in compressive strengths ranging from −1.67 and 6.22 MPa have been noticed.

The percentage of water used for the grout preparation is an important factor in influencing the mechanical performance of the composite sample. Therefore, whenever fiber is used during the composite mortar fabrication some amount of extra water is necessary for the mixture preparation.

Keywords

natural fiber composite mortar, jute fiber composite mortar, jute fiber composite mortars mechanical properties, DIC analysis

1 Introduction

In recent years, the craze to re-discover traditional building materials can be found among researchers and scientists, while sustainability and environmental protection are the main targets of their research activities. Traditionally, houses were always built with locally available natural raw materials, but only from the end of the nineteenth century the industrialized building materials like concrete, steel, and man-made (organic and synthetic) fibers dominate the Construction and Building (C&B) sector [1].

Mainly steel and synthetic (glass, carbon, polyvinyl, polyolefin, polypropylene, etc.) are used for the Fiber Reinforced Concrete (FRC), and sometimes natural fibers are also used for this purpose [2, 3]. For structural and non-structural strengthening, retrofitting, or upgrading, man-made fibers like glass [4–6], carbon [7], basalt [8–10], etc. are used as fiber composites and Fiber Reinforced Polymers (FRP) are used. Whereas for masonry retrofitting or upgrading, the use of glass [11, 12], carbon [13–15], basalt [16–18], steel [19], polypropylene [20] Textile-Reinforced Mortar (TRM) systems can be found in the literature. The man-made fibers are widely used, and their vast applicability is due to their higher strength and durability [21], moreover, these fibers are widely studied, and specific standards are available for their use and applications.

Notably man-made (organic and inorganic) fibers could be detrimental to human health, as well as to the nature and

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ecosystem, as these fibers are not biodegradable [22]. These fibers are made from non-renewable sources and their production processes are not ecologically friendly [22].

The C&B sector is directly and indirectly responsible for global warming and environmental pollution, it emits to the environment about 39% (globally) and 3% (in the EU) of the total CO_2 [23–25]. At the same time, Construction and Demolition (C&D) also produces (the majority goes to landfill) about 180 tons of waste every year [26]. Therefore, the use of Naturals Fibers (NF) in the C&B sector gaining importance due to having a lower environmental footprint [27] when compared with man-made fibers. On the other hand, natural fibers are bio-degradable, recyclable, relatively low in cost of production and processing, easily available, and at the same time, these fibers have good thermal and mechanical properties [28].

Various concepts already been experimented around the globe, and the applicability of natural fiber as building materials, like NFRC [29], composite and mortars [30, 31], NFRP (Jute, Sisal, Hemp and Flax [32]) and NFTRM (flax [33, 34], jute [33], hemp [35]) have been studied in these last few years with the aim these to be used for structural and/or thermal strengthening. There are some pros (low density, high specific strength, and stiffness, low environment impact, etc.) and cons (lower durability, lower strength, high moisture absorption, etc.) for natural fiber composites, as reported in [36], whereas the comparison with synthetic fibers can be found in [37]. Natural fibers have higher insulation capacity [37, 38] when compared with synthetic fibers, and when considered the global sustainability, recyclability, and biodegradability of the natural fiber composite or insulation panels are ideal for use as thermo-acoustic insulating building materials [30].

It has been highlighted that for natural fiber composite mortar with the increase of fiber percentages (with respect to the dry mortar mass) the flexural and compression strength reduces, on the other hand, the strain energy increases significantly which helps in dissipating the applied load energy [31].

It is quite difficult to measure the crack and crack patterns using conventional instruments like displacement sensors or strain gauges, therefore Digital Image Correlation (DIC) is an important tool to measure the crack dimensions and analysis the crack patterns (provided by DIC software) and being a non-contact fill-filed measuring procedure, is getting popular among scientists and researchers.

Notably, the DIC was already in use in the 1980s [39], it is an optical method to measure 2D or 3D coordinates for evaluation of required mechanical behaviors [40] and structural properties [41]. While the working principle of the DIC depends on analyzing the initial and final pictures, before and after the deformation of the target sample, respectively [42].

The present experimental work investigates the effect of water on the mechanical performance of the jute fiber composite mortar samples when the same amount of water has been used, as has been used for the mortar without fiber. Whereas the DIC method has been used to analyze and determine the cracks opening (mm) in the deformed specimens, before reaching the ultimate displacement point, during the flexural tests. For the DIC analysis, a very popular GOM correlate software has been used. Notably, this is a continuation of the research activities conducted in [31].

After a brief introduction, the detailed experimental procedure is explained in the material and method section. Thereafter the outcomes are highlighted in the result section and the final observations are reported in the conclusion section.

2 Material and methods

During this experimental campaign, the flexural strength, compression strength, and strain energy of each composite mortar type were analyzed, and later these values were compared with the mortar samples of the same fiber percent (with respect to the dry mortar mass) and fiber lengths, can be found in of the author's previous work [31].

2.1 Materials

2.1.1 Raw jute fibers

The jute fiber of Bangla Tosha – Corchorus olitorius (golden shine) origin has been used during this experimental campaign. The raw fibers on average are 3.5 m long and have been collected from a village of West Bengal, India. The mechanical behavior and physical properties of these fibers have been evaluated by the authors in [43] and can be found in Table 1.

For composite mortar preparation, the jute fibers were cut into 30 mm, 10 mm, and 5 mm fiber lengths (Fig. 1).

Table 1 Jute fiber properties [43]

Tensile strength	Max. axial strain	Stain energy	Elastic modulus
215 MPa	0.0131	0.77 N mm	16.97 GPa

(a) (b) (c)

Fig. 1 Jute fiber: (a) 30 mm; (b) 10 mm; and (c) 5 mm

2.1.2 Mortar

The mortar is nominated as Structural Mortar (SM), it is a premixed mortar for masonry and it is constituted with hydraulic binders and selected aggregates. The compressive strength, shear strength and dry density are about 10 MPa, 0.15 MPa and 1545 kg/m^3, respectively.

2.2 Test procedure

2.2.1 Composite mortar preparation

The composite samples were prepared by using various combinations (Table 2) of jute fiber lengths (30 mm, 10 mm and 5 mm) and for 0.5% and 1% fiber (with respect to the dry mortar mass) (Fig. 2(a)).

Samples are labeled in Table 3 MS identifies it as structural mortar, x signifies the casting number, whereas F for fiber, then fiber percentages (0.5% and 1%) and fiber lengths (30 mm, 10 mm and 5 mm), while My is the Mold and its number, and ending with the sample and its number i.e., Sz.

For example, a composite mortar sample MS1(SW) F0.5(10)M1S1 (Fig. 1) can be decoded as structural mortar (MS) has been used for the composite preparation with casting number 1, where the amount of water, fiber percentage (with respect to the dry mortar mass) and fiber length used for its preparation is equal to SW (Table 3), 0.5% and 10 mm, respectively, and at the end it tells that the mold number 1 has been used to cast the sample number 1.

For convenience, in the following sections, the composite mortar samples prepared with SW will be expressed as MS(SW).

During this experimental phase, the amount of water used for all combinations and grout preparation is exactly equal in quantity (Table 4). The Same Water (SW) is the equivalent amount of water that has been used for the normal mortar sample without fiber nominated as MS (no fiber) and reported in [31].

In this case, the effect of the water on fiber, when jute fiber comes in contact with water as reported in [43] has not been considered.

EN 1015-2:2007 [44] and EN 1015-3:2007 [45] have been considered as reference documents for the grout preparation and workability test, respectively.

During the composite mortar preparation phase, jute fiber (in combinations as mentioned in Table 2) and the dry mortar were mixed without any water for about 30 seconds inside a mixture. Thereafter water (amount as mentioned in Table 4) was poured continuously in small amounts and the mixture was stirred for about 7 mins (Fig. 2 (b)). After the mixtures were prepared, the grouts were subjected to shaking table tests (Fig. 2 (c), (d) and (e)) to evaluate their workability, when the subjected grout was in at fresh state.

During the shaking table test, the spreading diameters of the jute fiber composite mortars were compared with the reference mortar (SM). Acceptability of the composite mortars was determined when the average variation range of ±10% between two consecutive tests was obtained, see Table 5.

Mainly two molds (Fig.2 (f) and (g)) were used to cast six samples (of dimensions 160 mm × 40 mm × 40 mm), which are to be used for the mechanical tests. After the samples were prepared, the samples along with mold were placed inside plastic bags for the first two days. Samples were taken out from the molds on the 3rd day, from the day of casting and then they were re-placed inside another plastic bag for 5 days (Fig. 2 (h)). After this controlled drying (corresponding from the 2nd to 8th day) the samples were taken out from the plastic bags and placed in a room with an ambient temperature of 25 °C and relative humidity 65% (Fig. 2 (i)). Notably the EN 1015-11:2019 standard [46] has been followed for sample curing.

During this experimental campaign, MS(SW) samples are compared with two different composite mortar sample categories, distinctly MS(SAW) and MS, and specifications are highlighted in Table 6.

Table 2 Composite mixture and mortar samples: fiber percentage (with respect to the mortar mass) and fiber length combination scheme

		Fiber length		
		30 mm	10 mm	5 mm
Fiber percentage	0.5%	Yes	Yes	Yes
	1.0%	Yes	Yes and No*	Yes and No*

Note: Yes represents the grout preparation and No represents i.e., no samples were prepared due to the mixture-composition failing the workability test.

2.3 Evaluation of mechanical properties

On the 28th day from the sample casting date, the mechanical properties of the jute fiber composite mortar samples (160 × 40 mm × 40 mm) were evaluated through flexural and compression tests. The dimensions of each sample

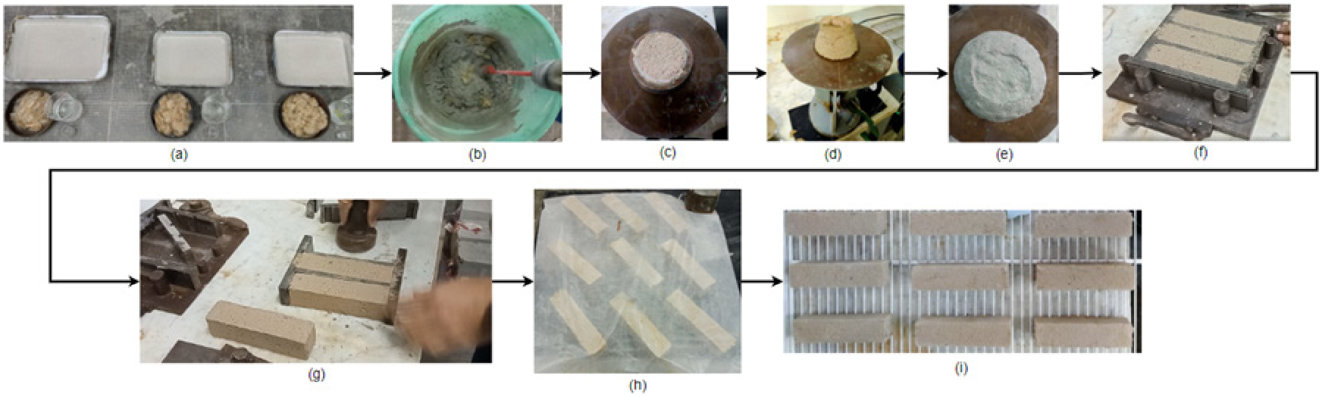

Fig. 2 Composite mortar samples preparation process: (a) Mortar, jute fibers (30 mm, 10 mm, and 5mm) and water; (b) composite mortar mixture; (c) mortar inside the brass mold; (d) mortar without brass mold; (e) spread mortar after the test; (f) casting of samples; (g) samples extraction after 3rd day from casting day; (h) samples put in plastic for another 5 days; and (i) samples left for natural drying

Table 3 Composite mortar identification scheme

		Fiber length		
		30 mm	10 mm	5 mm
Fiber percentage	0.5%	MSx(SW)F0.5(30)MySz	MSx(SW)F0.5(10)MySz	MSx(SW)F0.5(5)MySz
	1.0%	MSx(SW)F1(30)MySz	MSx(SW)F1(10)MySz	MSx(SW)F1(5)MySz

Table 4 Dry mortar mix to water proportion

Sample nomenclature	Mortar (without and with fiber)	Water
MS (No fiber) [31].		
MS(SW)F0.5(5), MS(SW)F0.5(10) and MS(SW)F0.5(30)	85.00%	15.00%
MS(SW)F1(5), MS(SW)F1(10) and MS(SW)F1(30)		

Note: fibers are added with respect to the dry mortar mass.

Table 5 Shaking table test of the jute fiber composite mortars

Reference sample	Reference value
MS (no fiber) [31]	164 mm
Tested samples	Change in spreading diameter values with respect to ± 10% of the MS (no fiber)
MS(SW)F0.5(5)	(minus) 1.11%
MS(SW)F0.5(10)	(minus) 3.23%
MS(SW)F0.5(30)	(minus) 3.96%
MS(SW)F1(5)	No samples were prepared*
MS(SW)F1(10)	No samples were prepared*
MS(SW)F1(30)	(minus) 2.63%

Note: For MS (no fiber) mechanical properties see [31].
* The mixture-composition failed the workability test.

were measured before starting the tests, and the information was used to calculate the flexural and compressive values.

A universal displacement-controlled machine (Fig. 3) with a maximum load capacity of 4.9 kN (sensitivity of 0.02 kN) has been used for the three-point bending flexural test, following the standard EN 1015-11:2019 [46]. Tests were performed with a displacement rate of 1.5 mm/min.

For measuring loads and corresponding displacements, a load cell of class 1 (with maximum capacity of 50 kN and nominal sensitivity of 2 mV/V) and a Linear Variable Displacement Transducer (LVDT) (with max. measuring length of 50 mm, nominal sensitivity of 2 mV/V and linearity –<0.10% of span) have been used, respectively.

Subsequently after flexural tests, the remaining two collapse parts of each sample have been used for the compression strength tests. The compression strength tests (Fig. 4) were conducted using another universal load-controlled machine with a maximum load capacity of 100 kN, tests

Table 6 Comparison between different composite mortars

	Sample prepared	Case 2	Case 1
Nomenclature	MS(SW)	MS(SAW)	MS (composite)
Full form	Structural Mortar (Same Water)	Structural Mortar (Same Average Water)	Structural Mortar (composite)
Comparison combinations (0.5% and 30 mm; 0.5% and 10 mm; 0.5% and 5 mm; 1.0% and 30 mm; 1.0% and 10 mm; and 1.0% and 5mm	Fiber percentages (0.5% and 1.0%) and fiber lengths (30 mm, 10 mm and 5 mm).	Fiber percentages (0.5% and 1.0%) and fiber lengths (30 mm, 10 mm and 5 mm).	Fiber percentages (0.5% and 1.0%) and fiber lengths (30 mm, 10 mm and 5 mm).
Distinction	For all the above combinations (fiber percentage and fiber length) amount of water used for the composite mortar preparation is equivalent to or the same as the amount of the Reference samples without fiber (see Table 5).	While in this case, the amount of water used for the composite mortars, is the average (used for grout with 30 mm, 10 mm, and 5 mm) amount of water used during Case 1 [31].	In [43] it has been proved that jute fiber, when comes in contact with water, has the ability to absorb as well as trap some extra water collectively. Therefore, during the composite mortar preparation, additional water was used based on the fiber lengths (30 mm, 10 mm, and 5 mm) [31] used in the mixture.

Note: SW is the Same Water and SAW is the Same Average Water.

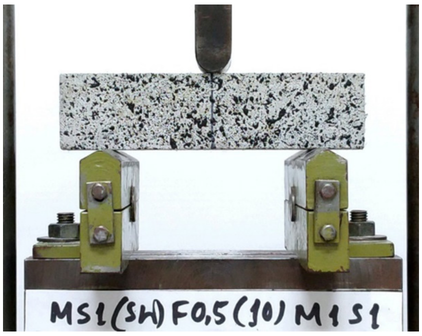

Fig. 3 Jute fiber composite mortar "MS1(SW)F0.5(10)M1S1" flexural strength test

Fig. 4 Jute fiber composite mortar "MS1(SW)F0.5(30)M1S1" compressive strength test

were performed following the EN 1015-11:2019 standard [46]. Fig. 5 shows three samples with 0.5% fiber after flexural strength test failures, whereas these presented samples have fiber lengths of 30 mm (Fig. 5 (a)), 10 mm (Fig. 5 (b)), and 5 mm (Fig. 5 (c)), respectively.

2.4 DIC analysis

The samples are prepared for the DIC analysis according to [39] and [47]. While preparation and measurements of the samples, and the analysis of the displacement or deformation of the target specimen using the DIC system were done as follows:

- Surface preparation: before starting the tests, the surface of the specimen was tinted with white paint, and after drying the black dots/sprinkles had to be stochastically sprayed on the white surface, as in Fig. 3.
- Software and camera calibration: Through DIC analysis software it is possible to define the quality of the analyzing pictures. Therefore, to obtain the best DIC results, the camera spatial resolution and the working distance between the camera(s) and the target object are correctly calibrated.
- For DIC analysis the camera is mounted exactly in front and perfectly parallel to the targeted center of the surface (Fig. 6). The camera used for the DIC analysis has a resolution of 1920 × 1080 pixels. While the focal distance has been measured around 200 cm. Two artificial lights were also used to have uniform light on the target surface, to have better quality of pictures for DIC analysis.
- Illumination: Light adjustment is an important factor for taking good pictures, therefore two high-intensity illumination bulbs have been used for this purpose (Fig. 6).
- Images capturing: It is important to note that picture taking interval should be synchronized with the load-displacement measuring instrument, whereas

Fig. 5 Jute fiber composite mortar samples: (a) MS1(SW)F0.5(30)M1S1; (b) MS1(SW)F0.5(10)M1S3; and (c) MS1(SW)F0.5(5)M1S2 after the flexural strength test failures

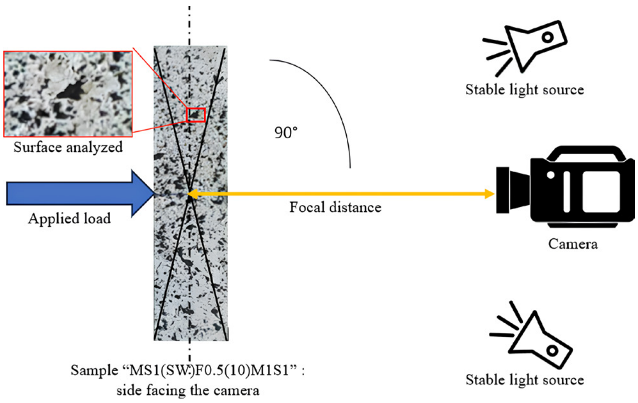

Fig. 6 2D DIC setup: sample MS(SW)F0.5(10)M1S1

the acquisition time interval was to be 0.5 seconds.

- DIC analysis: The GOM correlate software has been used for this purpose. A total of 15 pictures were selected for the DIC analysis (Fig. 7), for the subjected sample. The pictures have been selected from various phases, pictures 1 represents the point of zero loads, whereas picture 6 represents the peak load (at this point the sample collapsed, and a drop in the graph can be seen), subsequently pictures from 7 to 15 represents post-peak phases, where load gradually decrease and crack in samples increase until ultimate state represents with picture 15.
- Visualization of the results: Notably through this DIC analysis the crack opening distances between two broken parts at maximum displacement point are measured. Later this data corresponding to different fiber percentages (with respect to the dry mortar mass) and fiber length combinations were compared.

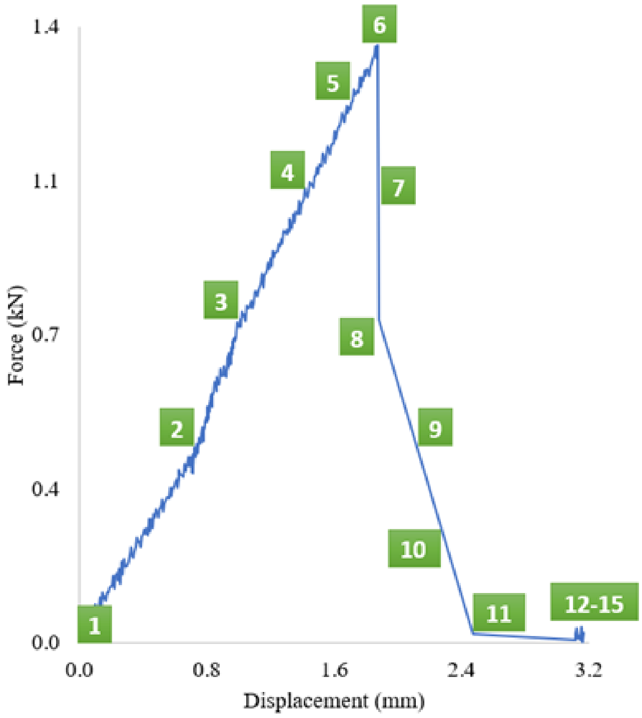

Fig. 7 Selected pictures underlined with number in green boxes, on a force-displacement curve of the sample MS(SW)F0.5(10)M1S1

3 Results

3.1 Mechanical properties

The experimental flexural properties of the jute fiber composite mortars "MS(SW)" are reported in Tables 7 and 8. Notably, a total of six samples of each type of jute fiber composite mortar were used for flexural strength tests, whereas a total of twelve samples were used for compressive strength tests.

The presence of fiber and its percentage (with respect to the mortar mass) and length directly affect the performance of the "MS(SW)" composite mortars, exactly in the same way authors have demonstrated in the previous work [31], the longer fibers demonstrate better mechanical performance in comparison to shorter ones. Notably, the strain energy (Table 7) as well as the flexural strength (Table 8) decrease with the decrease in fiber length. Results in Table 8 have been obtained considering the classical beams theory.

Figs. 8 and 9, present the force-displacement curves of some of the selective samples. The enclosed yellow part of the force-displacement curves represents the strain energy (kN mm).

Table 7 Flexural test properties: the deflection and strain energy capacity of the MS samples with the same water

	Deflection (d) corresponding to the peak load point		Strain energy (ft)	
	Mean	Co.V	Mean	Co.V
	(mm)	(%)	(kN mm)	(%)
MS(SW)F0.5(5)	1.85	2.32	1.39	5.36
MS(SW)F0.5(10)	1.72	10.81	1.28	18.03
MS(SW)F0.5(30)	2.01	8.20	1.82	13.86
MS(SW)F1(5)	No samples were prepared*			
MS(SW)F1(10)	No samples were prepared*			
MS(SW)F1(30)	2.09	15.41	1.81	15.33

* The mixture-composition failed the workability test.

Table 8 Flexural test properties: stress and strain of the MS samples with the same water

	Flexural stress (σ)		Flexural strain (ε)		Moment of inertia (I)	
	Mean	Co.V	Mean	Co.V	Mean	Co.V
	(MPa)	(%)		(%)	(mm^4)	(%)
MS(SW)F0.5(5)	3.18	0.73	0.04	2.58	236424.26	0.97
MS(SW)F0.5(10)	3.04	9.71	0.04	10.92	234688.15	0.52
MS(SW)F0.5(30)	3.65	7.86	0.04	8.37	220435.97	1.20
MS(SW)F1(5)	No samples were prepared*					
MS(SW)F1(10)	No samples were prepared*					
MS(SW)F1(30)	3.60	10.46	0.04	15.40	223715.80	0.64

* The mixture-composition failed the workability test.

Fig. 10 presents a comparison between the stain energy and the flexural strength values of the MS(SW) composite mortars and MS(no fiber) (as mentioned in Fig. 10 and [31]), as well as with MS(SAW) composite mortars (as mentioned in Fig. 10 and [31]).

When MS(SW) composite mortar samples are compared with MS composite mortars, both of 0.5% (with respect to the dry mortar mass) category (i.e., for 5 mm and 10 mm fiber lengths) , it has been observed that due to the use of SW, the strain energy increase (see Fig. 10, calculated as MS(SW)F0.5 – MSF0.5) by 0.71 for 5 mm fiber length, 0.70 kN mm for 10mm fiber length and 0.92 kN mm for 30 mm fiber length.

Whereas the flexural strength reduced (see Fig. 10, calculated as MS(SW)F0.5 – MSF0.5) by −1.86 MPa for 5 mm fiber length, −2.79 MPa for 10 mm fiber length, and −2.63 MPa for 30 mm fiber length.

Whereas when MS(SW) composite mortar samples are compared with MS(SAW) composite mortar samples, and both of 0.5% (with respect to the dry mortar mass) category, the improvement (see Fig. 10, calculated as MS(SW)F0.5 – MS(SAW)F0.5) in both strain energy and flexural strength have been obtained by 1.03 kN mm and 1.10 MPa for 5 mm fiber length, 0.81 kN mm and 1.12 Mpa for 10 mm fiber length and 1.45 kN mm and 1.75 Mpa for 30 mm fiber length.

When MS(SW) composite mortar samples are compared with MS composite mortars, and both of 1% (with respect to the dry mortar mass) category, it was observed that the SW structural composite mortars have higher strain energy of 0.92 kN mm and lower flexural strength of −1.47 Mpa for 30 mm fiber length (see Fig. 10, calculated as MS(SW)F1 – MSF1).

Conversely, when MS(SW) composite mortar samples are compared with MS(SAW) composite mortar samples, both of 1% (with respect to the dry mortar mass) category, the SW structural composite mortar samples were found to have higher strain energy and flexural strength of 1.10 kN mm and 0.24 MPa, respectively, (see Fig. 10, calculated as MS(SW)F1 – MS(SAW)F1.

Table 9 presents the compressive strength values obtained for the structural composite mortar samples "MS(SW)" prepared with same water (SW) amount. It is clearly noticeable that for samples with 0.5% jute fiber (Table 9), with the reduction in fiber length (from 30 mm to 5 mm) the compressive strength also decreased from 12.74 to 11.66, respectively. Whereas with the increment in fiber percentages, the compressive strength also reduces. Similarly,

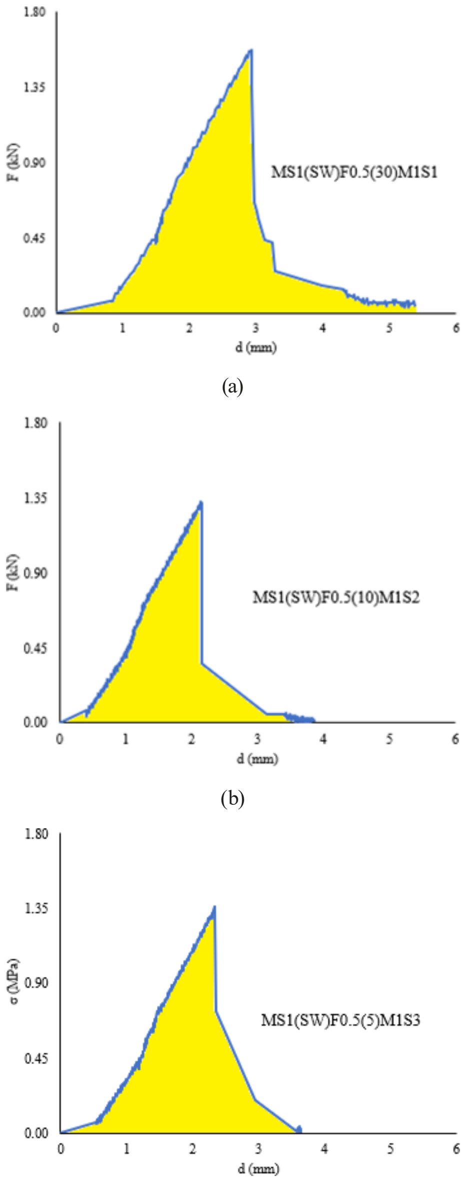

Fig. 8 The force (F) - displacement (δ) curves of samples with 0.5% of fiber: (a) MS1(SW)F0.5(30)M1S1; (b) MS1(SW)F0.5(10)M1S2; and (c) MS1(SW)F0.5(5)M1S3

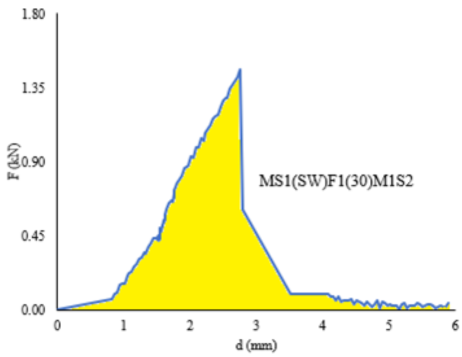

Fig. 9 The force (F) – displacement (δ) curves of samples with 1.0% of fiber: MS1(SW)F1(30)M1S2

samples with a higher percentage of jute fiber (MS(SW) F1(30)) i.e., with 1.0% of jute fiber and 30 mm of fiber length), the compressive strength reduced about 0.10 MPa in average, when compared with the sample (MS(SW) F0.5(30)) with 0.5% of jute fiber and 30 mm of fiber length.

When MS(SW) composite mortar samples are compared with MS composite mortars, both of 0.5% (with respect to the dry mortar mass) category, it has been observed that the application of SW induced a reduction in the compressive strengths of the structural composite mortar samples (see Fig. 11, calculated as MS(SW)F0.5 – MSF0.5) category by −10.17 MPa for 5 mm fiber length, −12.02 MPa for 10 mm fiber length and −14.01 MPa for 30 mm fiber length. Similarly, the compressive strength has also reduced (see Fig. 8, calculated as MS(SW)F1 – MSF1) for the 1% fiber (with respect to the dry mortar mass) category by −5.40 MPa for 30 mm fiber length. While just the opposite happened for the MS(SW) structural composite mortar samples compared with MS(SAW) structural composite mortar samples, both of 0.5% (with respect to the dry mortar mass), the compressive strength increased (see Fig. 11, calculated as MS(SW)F0.5 – MS(SAW)F0.5) by 4.13MPa for 5 mm fiber length, 5.66 MPa for 10 mm fiber length and 6.22 MPa for 30 mm fiber length.

Whereas MS(SW) composite mortar samples compared with MS(SAW) composite mortar samples, both of 1% fiber (with respect to the dry mortar mass) category, highlighted the compressive strength reduction (see Fig. 11, calculated as MS(SW)F1 – MS(SAW)F1) by −1.67 MPa for 30 mm fiber length.

As previously mentioned, the two grout mixture compositions (MS(SW)F1(5) and MS(SW)F1(10)) did not pass the shaking table tests, therefore it also justifies and validates the previous research works conducted by authors [31] and [43] and, i.e., with the increase of fiber percentages (with respect to the dry mortar mass) and with reduction of fiber lengths, the need of water for grout preparation increases because fibers not only absorb water by itself but also when they come in contact with water they form fiber balls and behaves like a sponge and trap extra water in the cavity, as reported in [43].

3.2 DIC analysis

DIC analysis has been done using the GOM correlate software. Figs. 12 to 15 represent DIC analysis of the crack opening patterns at the ultimate displacement state of the applied load, for the samples MS(SW)F0.5(30) M1S1, MS(SW)F0.5(10)M1S1, MS(SW)F0.5(5)M1S3 and

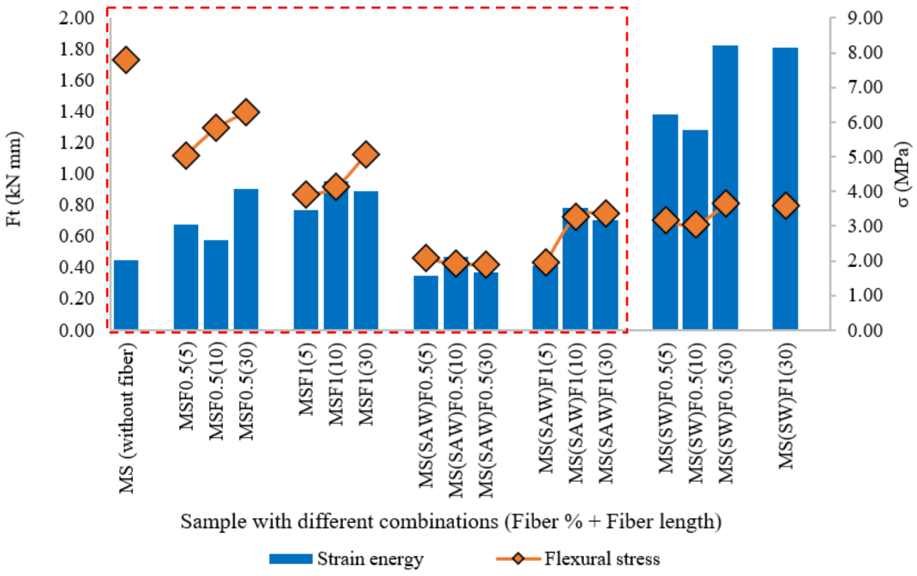

Fig. 10 Jute fiber thermal composite mortars flexural test results: SW vs. SAW and MS and different percentage of water used for different fiber percentage and length combinations

Table 9 Compressive strength for the SM with same water

	Mean (Mpa)	Co.V (%)
MS(SW)F0.5(5)	11.66	4.44
MS(SW)F0.5(10)	12.22	4.90
MS(SW)F0.5(30)	12.74	4.62
MS(SW)F1(5)	No samples were prepared*	
MS(SW)F1(10)	No samples were prepared*	
MS(SW)F1(30)	12.64	5.30

* The mixture-composition failed the workability test.

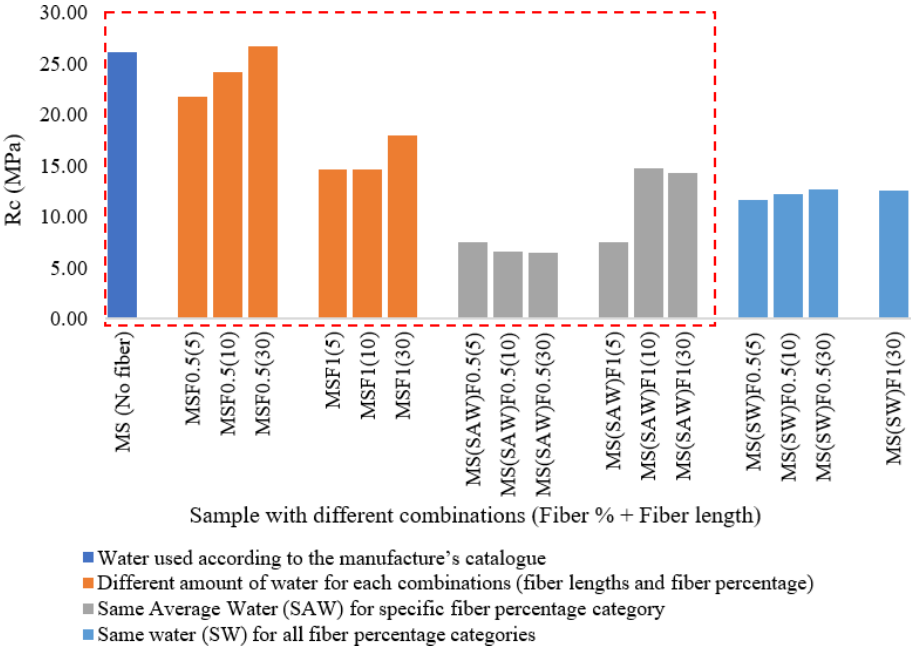

Fig. 11 Jute fiber thermal composite mortars compression test results: SW vs. SAW and MS and different percentage of water used for different fiber percentage and length combinations

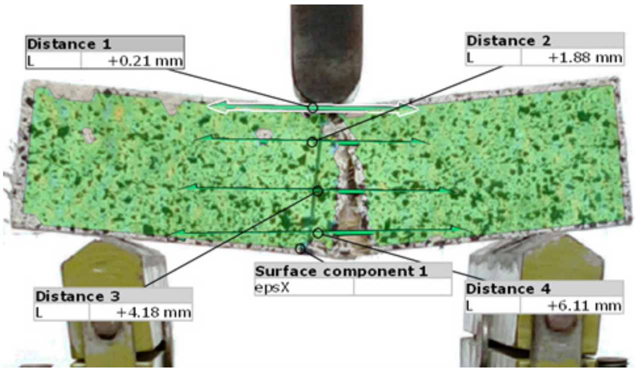

Fig. 12 DIC analysis of the sample MS1(SW)F0.5(30)M1S1

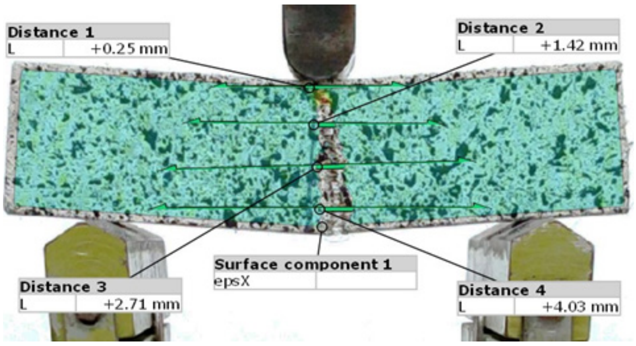

Fig. 13 DIC analysis of the sample MS1(SW)F0.5(10)M1S1

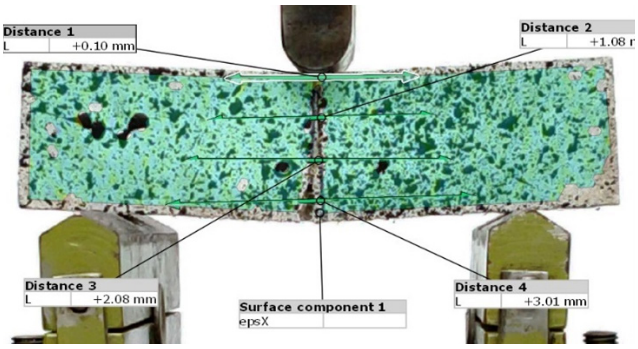

Fig. 14 DIC analysis of the sample MS1(SW)F0.5(5)M1S3

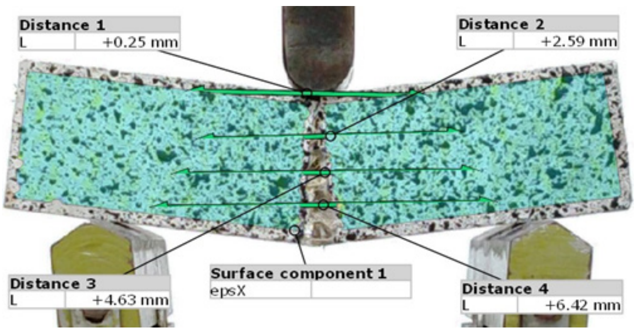

Fig. 15 DIC analysis of the sample MS(SW)F1(30)M1S1

MS(SW)F1(30)M1S1, respectively. Fig. 16 represents the progressive crack dimension of the sample MS(SW) F0.5(10)M1S1 with respect to each picture from 1 to 15. Similar types of graphs are also obtained for other samples.

It is evident that the longer fibers help in binding/holding the broken parts together avoiding complete collapse of the sample. This can be demonstrated, when the MS(SW) samples with 0.5% fiber (with respect to the mortar mass) and fiber lengths 30 mm, 10 mm and 5 mm, respectively are compared, it is clearly noticeable that in the sample with 30 mm fiber length, the crack/openings are 34% and 50% higher than that of samples imbodied with 10mm and 5mm long fiber, respectively.

When two MS(SW) samples with similar fiber lengths (30 mm) but with different fiber percentages i.e., 0.5% and 1.0% fiber (with respect to the mortar mass) are compared, then it has been observed that MS(SW) with a higher percentage of fiber in it has the wider crack opening, which is about 5% larger with respect to other.

This clearly justifies that the samples with longer fibers have higher strain energy (validates the observations of Section 3.1) as these longer fibers hold the broken parts longer, so as helps in dissipating the energy of the applied load.

4 Conclusions

This research work is a continuation of a previous experimental campaign about the use of recycled jute fiber composite mortar for thermal and structural retrofitting (for details see [1]). The results presented here demonstrate the effect of water on the mechanical performance of the jute fiber composite mortar samples with SW, i.e., when the same amount of water has been used:

During this campaign, samples are prepared with the Same Water (SW), which is exactly the same amount that has been used for the reference sample (without fiber) preparation (see [31]).

Interestingly higher strain energy capacities have been observed for all Same Water (SW) samples when compared with Same Average Water (SAW) samples and MS composite mortar samples. This improvement in strain energy could demonstrate to be a distinctive factor during an earthquake when it is necessary to dissipate the effects of the extreme load.

The Same Water (SW) samples exhibited a reduction in flexural strengths in all category combinations (fiber percentages and fiber lengths), when compared with MS-composite mortar samples. On the contrary, improvements in flexural strengths have been observed in comparison with the Same Average Water (SAW) samples.

Due to the application of Same Water (SW), the reduction in compressive strengths has been observed for all combinations (fiber percentages and finer lengths), when compared with the MS composite mortar samples.

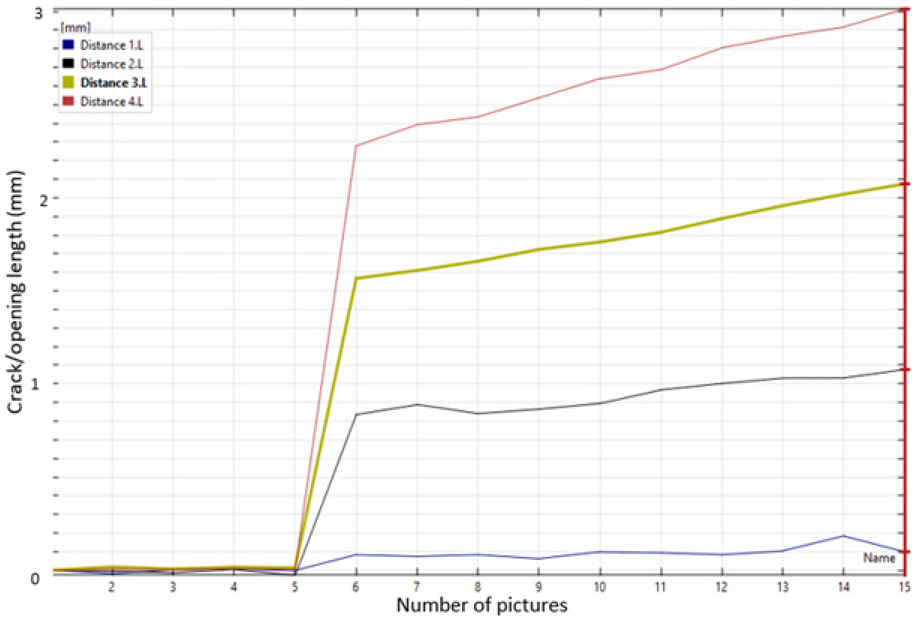

Fig. 16 Increase in crack/opening (mm) with progress from Picture 1 to picture 15; of the sample MS(SW)F0.5(10)M1S1

However, the Same Water (SW) samples exhibited superior compressive strengths when compared to the Same Average Water (SAW) samples.

Due to the presence of jute fiber (30 mm, 10 mm and 5 mm), all composite mortar samples have shown ductile behavior.

The crack patterns and opening (mm) that occurred during the flexural tests are analyzed using DIC method, and it is quite evident that the longer fibers help in binding/holding the broken parts together avoiding complete collapse of the sample. Therefore, during real-time earthquake cases, the risk to human life and overall damage could be minimized.

During the composite mortar fabrication, the percentage of water used for the grout preparation is an important factor and it influences the mechanical performance of the composite sample. Therefore, based on the experience gained during the previous and this current experimental campaign, it can be deduced that some amount of extra water is necessary to be added during the mixture/grout preparation.

The extra amount of water needs to be calculated in advance through the water absorption tests. Notably, no samples were prepared for the mixture-composition (a) 1.0% fiber and 5 mm fiber length, and (b) 1.0% fiber and 10 mm fiber length, due to grouts' workability test failure.

It is crucial to create a perfect composite mixture (mortar, fiber and water) during the grout preparation, as the right combination always determines the optimum performance of the samples. Further experiments to be scheduled based on knowledge from current and previous campaigns to explore wider aspects of jute as a composite fiber mortar.

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References

[1] Majumder, A., Stochino, F., Frattolillo, A., Valdes, M., Fraternali, F., Martinelli, E. "Sustainable Building Material: Recycled Jute Fiber Composite Mortar for Thermal and Structural Retrofitting", In: Computational Science and Its Applications – ICCSA 2022 Workshops, Malaga, Spain, 2022, pp. 657–669. ISBN 978-3-031-10544-9
https://doi.org/10.1007/978-3-031-10545-6_44

[2] Kheyroddin, A., Arshadi, H., Ahadi, M. R., Taban, G., Kioumarsi, M. "The impact resistance of Fiber-Reinforced concrete with polypropylene fibers and GFRP wrapping", Materials Today: Proceedings, 45, pp. 5433–5438, 2021.
https://doi.org/10.1016/j.matpr.2021.02.116

[3] Saleh, H. Rahman, R. O. A. (eds.) "Cement Based Materials", InTech, 2018. ISBN 978-1-78984-154-1
https://doi.org/10.5772/intechopen.71134

[4] Sreekumar Kavitha, S., Joseph, L., Madhavan, M. K., Jayanarayanan, K. "Comparative study of carbon and glass fiber reinforced polymer composites for the confinement of concrete columns", Materials Today: Proceedings, 2023.
https://doi.org/10.1016/j.matpr.2023.09.010

[5] Yıldırım, M., Bilir Özhan, H. "Residual Durability Performance of Glass Fiber Reinforced Concrete Damaged by Compressive Stress Loads", Periodica Polytechnica Civil Engineering, 67(2), pp. 392–401,2023.
https://doi.org/10.3311/PPci.21387

[6] Alsadey, S., Omran, A., Albakosuh A. "Strengthening of cylinders concrete confined with glass-reinforced polymer", In: 13th International Seminar on Industrial Engineering and Managmenet, Bandung, Indonesia, 2021, 080011
https://doi.org/10.1063/5.0108214

[7] Kizilkanat, A. B. "Experimental Evaluation of Mechanical Properties and Fracture Behavior of Carbon Fiber Reinforced High Strength Concrete", Periodica Polytechnica Civil Engineering, 60(2), pp. 289–296, 2016.
https://doi.org/10.3311/PPci.8509

[8] Padalu, P. K. V. R., Singh, Y., Das, S. "Cyclic two-way out-of-plane testing of unreinforced masonry walls retrofitted using composite materials", Construction and Building Materials, 238, 117784, 2020.
https://doi.org/10.1016/j.conbuildmat.2019.117784

[9] Khan, M., Cao, M., Ai, H., Hussain, A. "Basalt Fibers in Modified Whisker Reinforced Cementitious Composites", Periodica Polytechnica Civil Engineering, 66(2), pp. 344–354, 2022.
https://doi.org/10.3311/PPci.18965

[10] Chaudhari, R. S., Gorade, S. B. "Investigation on use of basalt fiber reinforced polymer for improvement in flexural strength of reinforcement concrete", World Journal of Advanced Engineering Technology and Sciences, 8(2), pp. 55–61, 2023.
https://doi.org/10.30574/wjaets.2023.8.2.0072

[11] Qureshi, M. F., Sheikh, S. A. "Shear behaviour of GFRP strengthened RC beams at elevated temperatures", Construction and Building Materials, 368, 130371, 2023.
https://doi.org/10.1016/j.conbuildmat.2023.130371

[12] Akhoundi, F., Vasconcelos, G., Lourenço, P., Silva, L. M., Cunha, F., Fangueiro, R. "In-plane behavior of cavity masonry infills and strengthening with textile reinforced mortar", Engineering Structures, 156, pp. 145–160, 2018.
https://doi.org/10.1016/j.engstruct.2017.11.002

[13] Kim, H.-S., Truong, G. T., Park, S.-H., Choi, K.-K. "Tensile Properties of Carbon Fiber-Textile Reinforced Mortar (TRM) Characterized by Different Anchorage Methods", International Journal of Concrete Structures and Materials, 12(1), 73, 2018.
https://doi.org/10.1186/s40069-018-0296-x

[14] Krevaikas, T. D. "Experimental study on carbon fiber textile reinforced mortar system as a means for confinement of masonry columns", Construction and Building Materials, 208, pp. 723–733, 2019.
https://doi.org/10.1016/j.conbuildmat.2019.03.033

[15] Babaeidarabad, S., Caso, F. D., Nanni, A. "Out-of-Plane Behavior of URM Walls Strengthened with Fabric-Reinforced Cementitious Matrix Composite", Journal of Composites for Construction, 18(4), 04013057, 2014.
https://doi.org/10.1061/(ASCE)CC.1943-5614.0000457

[16] Hutaibat, M., Ghiassi, B., Tizani, W. "Flexural behaviour of concrete thin sheets prestressed with basalt-textile reinforcement", Construction and Building Materials, 404, 133213, 2023.
https://doi.org/10.1016/j.conbuildmat.2023.133213

[17] Caggegi, C., Ferrara, G., Lanoye, E., Nguyễn, Đ. B., Gabor, A., Martinelli, E. "Experimental Study on the Effectiveness of Masonry-Basalt TRM Reinforced Systems Characterized by Different Fiber Grid Densities", Key Engineering Materials, 747, pp. 266–273, 2017.
https://doi.org/10.4028/www.scientific.net/KEM.747.266

[18] Ferrara, G., Caggegi, C., Gabor, A., Martinelli, E. "Experimental Study on the Adhesion of Basalt Textile Reinforced Mortars (TRM) to Clay Brick Masonry: The Influence of Textile Density", Fibers, 7(12), 103, 2019.
https://doi.org/10.3390/fib7120103

[19] Garcia-Ramonda, L., Pelá, L., Roca, P., Camata, G. "In-plane shear behaviour by diagonal compression testing of brick masonry walls strengthened with basalt and steel textile reinforced mortars", Construction and Building Materials, 240, 117905, 2020.
https://doi.org/10.1016/j.conbuildmat.2019.117905

[20] Mustafaraj, E., Yardim, Y., Corradi, M., Borri, A. "Polypropylene as a Retrofitting Material for Shear Walls", Materials, 13(11), 2503, 2020.
https://doi.org/10.3390/ma13112503

[21] Ramesh, M., Rajeshkumar, L. N., Srinivasan, N., Kumar, D. V., Balaji, D. "Influence of Filler Material on Properties of Fiber-Reinforced Polymer Composites: A Review", e-Polymers, 22(1), pp. 898–916, 2022.
https://doi.org/10.1515/epoly-2022-0080

[22] Majumder, A., Stochino, F., Fraternali, F., Martinelli, E. "Seismic and Thermal Retrofitting of Masonry Buildings with Fiber Reinforced Composite Systems: A State of the Art Review", International Journal of Structural Glass and Advanced Materials Research, 5(1), pp. 41–67, 2021.
https://doi.org/10.3844/sgamrsp.2021.41.67

[23] OECE "Environment", [online] Available at: https://www.Oecd.Org/Environment/ [Accessed: 22 August 2023]

[24] Benzar, B.-E., Park, M., Lee, H.-S., Yoon, I., Cho, J. "Determining retrofit technologies for building energy performance", Journal of Asian Architecture and Building Engineering, 19(4), pp. 367–383, 2020.
https://doi.org/10.1080/13467581.2020.1748037

[25] EC "Energy Performance of Buildings Directive", [online] Available at: https://Energy.Ec.Europa.Eu/Topics/Energy-Efficiency/Energy-Efficient-Buildings/Energy-Performance-Buildings-Directive_en [Accessed: 22 August 2023]

[26] APPRICOD "Appricode guide: Towards Sustainable Plastic Construction and Demolition Waste Management in Europe", Association of Cities and Regions, Brussels, Belgium, 2006. [online] Available at: https://www.acrplus.org/images/pdf/document142.pdf [Accessed: 20 October 2023]

[27] Woigk, W., Fuentes, C. A., Rion, J., Hegemann, D., van Vuure, A. W., Dransfeld, C., Masania, K. "Interface properties and their effect on the mechanical performance of flax fibre thermoplastic composites", Composites Part A: Applied Science and Manufacturing, 122, pp. 8–17, 2019.
https://doi.org/10.1016/j.compositesa.2019.04.015

[28] Chand, N., Fahim, M. "Tribology of Natural Fiber Polymer Composites", Woodhead Publishing, 2020. ISBN 978-0-12-818983-2
https://doi.org/10.1016/C2018-0-04814-8

[29] Yooprasertchai, E., Wiwatrojanagul, P., Pimanmas, A. "A use of natural sisal and jute fiber composites for seismic retrofitting of nonductile rectangular reinforced concrete columns", Journal of Building Engineering, 52, 104521, 2022.
https://doi.org/10.1016/j.jobe.2022.104521

[30] Majumder, A., Achenza, M., Mastino, C. C., Baccoli, R., Frattolillo, A. "Thermo-acoustic building insulation materials fabricated with recycled fibers – Jute, Wool and Loofah", Energy and Buildings, 293, 113211, 2023.
https://doi.org/10.1016/j.enbuild.2023.113211

[31] Majumder, A., Stochino, F., Frattolillo, A., Valdes, M., Mancusi, G., Martinelli, E. "Jute fiber-reinforced mortars: mechanical response and thermal performance", Journal of Building Engineering, 66, 105888, 2023.
https://doi.org/10.1016/j.jobe.2023.105888

[32] Codispoti, R., Oliveira, D. V., Olivito, R. S., Lourenço, P. B., Fangueiro, R. "Mechanical performance of natural fiber-reinforced composites for the strengthening of masonry", Composites Part B: Engineering, 77, pp. 74–83, 2015.
https://doi.org/10.1016/j.compositesb.2015.03.021

[33] Trochoutsou, N., Di Benedetti, M., Pilakoutas, K., Guadagnini, M. "Mechanical Characterisation of Flax and Jute Textile-Reinforced Mortars", Construction and Building Materials, 271, 121564, 2021.
https://doi.org/10.1016/j.conbuildmat.2020.121564

[34] Ferrara, G., Caggegi, C., Martinelli, E., Gabor, A. "Shear capacity of masonry walls externally strengthened using Flax-TRM composite systems: experimental tests and comparative assessment", Construction and Building Materials, 261, 120490, 2020.
https://doi.org/10.1016/j.conbuildmat.2020.120490

[35] Menna, C., Asprone, D., Durante, M., Zinno, A., Balsamo, A., Prota, A. "Structural behaviour of masonry panels strengthened with an innovative hemp fibre composite grid", Construction and Building Materials, 100, pp. 111–121, 2015.
https://doi.org/10.1016/j.conbuildmat.2015.09.051

[36] Pickering, K. L., Efendy, M. G. A., Le, T. M. "A review of recent developments in natural fibre composites and their mechanical performance", Composites Part A: Applied Science and Manufacturing, 83, pp. 98–112, 2016.
https://doi.org/10.1016/j.compositesa.2015.08.038

[37] Asyraf, M. Z., Suriani, M. J., Ruzaidi, C. M., Khalina, A., Ilyas, R. A., Asyraf, M. R. M., Syamsir, A., Azmi, A., Mohamed, A. "Development of Natural Fibre-Reinforced Polymer Composites Ballistic Helmet Using Concurrent Engineering Approach: A Brief Review", Sustainability, 14(12), 7092, 2022.
https://doi.org/10.3390/su14127092

[38] Savio, L., Pennacchio, R., Patrucco, A., Manni, V., Bosia, D. "Natural Fibre Insulation Materials: Use of Textile and Agri-Food Waste in a Circular Economy Perspective", Materials Circular Economy, 4(1), 6, 2022.
https://doi.org/10.1007/s42824-021-00043-1

[39] Janeliukstis, R., Chen, X. "Review of digital image correlation application to large-scale composite structure testing", Composite Structures, 271, 114143, 2021.
https://doi.org/10.1016/j.compstruct.2021.114143

[40] Deák, P., Kowalik, M. "Composite Aircraft Joint Experimental Testing with Digital Image Correlation", In: 13th Research and Education in Aircraft Design Conference, Brno, Czech Republic, 2019, pp. 150–160. ISBN 978-80-214-5696-9
https://doi.org/10.13164/conf.read.2018.15

[41] Paul, S. C., Pirskawetz, S., Van Zijl, G. P. A. G., Schmidt, W. "Acoustic emission for characterising the crack propagation in strain-hardening cement-based composites (SHCC)", Cement and Concrete Research, 69, pp. 19–24, 2015.
https://doi.org/10.1016/j.cemconres.2014.12.003

[42] Liu, B., Yue, F., Chen, B., Man, X., Chen, L., Jaisee, S. "Study on bond performance, flexural and crack extension behavior of base concrete prisms strengthen with strain-hardening cementitious composites (SHCC) using DIC technology", Construction and Building Materials, 251, 119035, 2020.
https://doi.org/10.1016/j.conbuildmat.2020.119035

[43] Majumder, A., Stochino, F., Farina, I., Valdes, M., Fraternali, F., Martinelli, E. "Physical and mechanical characteristics of raw jute fibers, threads and diatons", Construction and Building Materials, 326, 126903, 2022.
https://doi.org/10.1016/j.conbuildmat.2022.126903

[44] UNE "EN 1015-2:2007 Methods of test for mortar for masonry—Part 2: Bulk sampling of mortars and preparation of test mortars", Spanish Association for Standardization (UNE), Madrid, Spain, 2007.

[45] UNE "EN 1015-3:2007 Methods of test for mortar for masonry - Part 3: Determination of consistence of fresh mortar (by flow table)", Spanish Association for Standardization, UNE, Madrid, Spain, 2007.

[46] BSI "EN 1015-11:2019 Methods of test for mortar for masonry Determination of flexural and compressive strength of hardened mortar", British Standards Institution (BSI), London, UK, 2019.

[47] Górszczyk, J., Malicki, K., Zych, T. "Application of Digital Image Correlation (DIC) Method for Road Material Testing", Materials, 12(15), 2349, 2019.
https://doi.org/10.3390/ma12152349