



Cellulosic Fabric-Reinforced Cementitious Matrix (FRCM): Ligaments, Treatments, and Employment

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Abstract

Fabric-reinforced cementitious matrix (FRCM) with synthetic reinforcements has been employed in a wide of precast products in the current market. However, FRCM employing cellulosic fibers has been limited in civil engineering applications due to the absence of a well-established standardization. Cellulosic textile structures present many advantages to strengthen cementitious composites, which depend on the type of natural fiber, forms that are organized (e.g., bundle fibers or twisted yarns), and ligaments. This study aimed to develop an overview of FRCM to identify how cellulosic textile has been designed and processed in research, according to type, shape, properties, durability, and matrix formulations. The main findings were as follows: (i) bundle fibers and low entangled yarns presented potential to increase the tensile properties; (ii) woven canvas prevailed in the cementitious composite applications; (iii) 3 and 4 layers of fabrics presented better mechanical performance than few layer samples; (iv) the alkaline treatment is one of most employment to improve the adherence; (v) to prevent cellulose degradation, resin coatings (epoxy) or pozzolan additions (silica, metakaolin, nanoclay, ashes from agricultural wastes) are employed. Future investigations are necessary to improve cellulosic FRCM; opportunities for study in textile area are proposed: enlargement of fabric technologies, hybrid fibers, machinery technology (3D fabrics, complex knit) adaptation to use cellulosic fibers, and new architectural design for cellulosic FRCM applications (curved forms and sizes).

Keywords Fabric-reinforced cementitious matrix · FRCM · Textiles · Treatments · Ligaments · Durability

Introduction

Cement-based materials are the most used sources of building sector. The sector demands significant waste generation, energy and material consumption. For these reasons, the use of more renewable resources strengthens the sustainability in construction, an alternative to reducing the energy expenditure and the emission of greenhouse gases (GHG), which can be an opportunity to use cellulosic materials (Ferrara et al., 2021; Onuaguluchi & Banthia, 2016).

Fabric-reinforced cementitious matrix (FRCM) with synthetic reinforcements has been employed in a wide of

precast products at the current market, mainly two main lines of goods: first, the architectural (non-load bearing), such as exterior cladding systems, façades, and wall panels; second, structural (loadbearing) elements, such as bridge and reinforcing cement pipes (Papanicolaou, 2016). Further applications are also possible, in view of use for masonry rehabilitation (de Carvalho Bello et al. 2019) and bear architectural structures, such as shell design buildings (Hegger et al., 2018).

However, FRCM employing cellulosic fibers has been limited in civil engineering applications due to the absence of a well-established standardization. But even so, these materials are being employed at building market goods (Sacconi et al., 2021), such as cement composites with autoclaved cellulose fibers, which are widely used in residential and commercial boards (siding, floor, and roofing) (Akhavan et al., 2017). The standardization is only a matter of time because for high-performance cementitious composite application was published RILEM TC 232-TDT recommendation, to measure the load-bearing behavior of tensile specimens made by straight fibers (carbon and AR-glass) and concrete

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matrix (RILEM Technical Committee, 2016; Tsangouri et al., 2019).

Fibers, yarns, and fabrics are textile materials, which have been used as composite reinforcements since World War II and are classified as: staple yarns (from natural fibers or cut synthetic fibers), continuous filaments (synthetic fibers), woven fabrics (2D), and advanced fabrics (3D) (Scardino, 1989).

Yarn is a group of fibers processed with torsion (twisted yarn) or without torsion (low entangled yarn), which have a substantial length and relatively small cross-section. In twisted yarns, the friction resulting from the torsion consolidates the constituent fibers. The process to produce a spun yarn from staple fibers is called spinning and involves a long chain of operations (Misnon et al., 2014).

Staple fibers are also used dispersed or oriented in the production of nonwoven fabrics, which can be joined by needling, thermoforming, or chemical methods. Another alternative is to use continuous yarns impregnated with resin and aligned in one direction (Misnon et al., 2014).

Two-dimensional fabrics (2D fabrics) can be woven by weaving (in looms) or knitting (in proper machinery), respectively, through interlacing or looping with the main direction in the warp or weft (Misnon et al., 2014).

The 2D fabrics produced by weaving on looms can present several options for ligaments or designs. The most traditional ones are: canvas (1×1), twill (2×1 , 3×1 , and variants), and satin (4×1 or greater and variants) ligaments, which can still vary in weight and number of weft or warp yarns (Yang et al., 2015). Satin fabric ligaments and multilayered 2D fabrics are usually used in high-performance polymer composites, such as in aircraft fuselage, in which high-strength fibers (e.g., carbon fiber) are employed (Archer et al., 2010; Yang et al., 2015).

The use of vegetable fiber reinforcement in cement-based materials started in the 1970s in order to substitute synthetic and asbestos fibers, moreover reduce raw-material costs and extend sustainability of the sector (Correia et al., 2020).

Recent desire to expand the composite usage has had a dramatic effect on global research, and textile reinforcement followed this trend, due to the possibility of a range of new applications and available textiles reinforcements (Ogin & Potluri, 2016). Textile structure presents many advantages to strengthen composites instead of dispersed fibers, due to widely of physical characteristics and additional (Aisyah et al. 2021; Misnon et al., 2014).

According to Aisyah et al. (2021) and Misnon et al. (2014), cellulosic textile materials present many advantages to composites application instead of dispersed fibers, due to fiber content, yarn type, and fabric ligament employment. In addition, several methods to preserve the integrity of cellulosic fabrics over time can be possibly applied to reinforced cementitious matrix (FRCM). Thus, this study

aimed to develop an overview of FRCM in order to identify how cellulosic textile has been designed and processed in research, according to type, shape, properties, durability, and matrix formulations.

Methodology

In the study, the literature review was based on keywords search in Scopus and Google Scholar (7 May 2021). The employed topics were “cellulose textile, fabric or yarns,” “cementitious matrix,” “fabric reinforced cementitious matrix,” and “composites.” Thus, with articles and reviews found, they were selected by their relevance with this study aims.

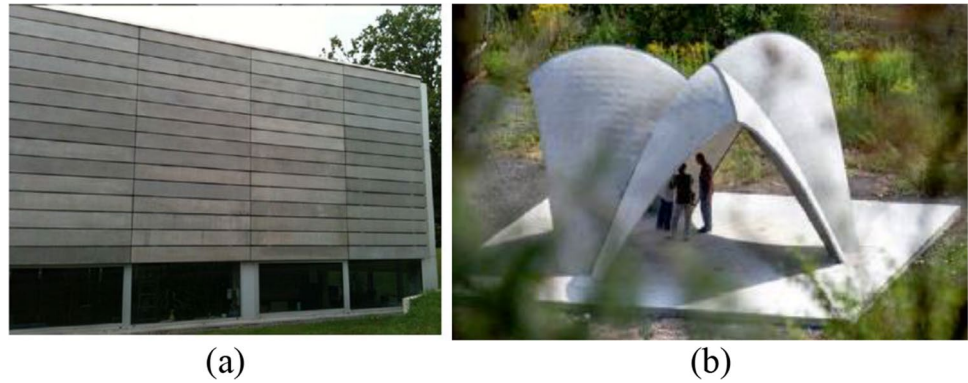
Lastly, the main issues were identified, which address some topics: yarns and bundle fibers reinforce composites, cellulosic fabrics reinforce cementitious composite, cellulosic fabric and cementitious matrix adherence or bonding, and durability of natural fabric. Therefore, this article was divided into the following subheadings: (i) FRCM applications; (ii) textile materials; (iii) natural fibers; (iv) pre-treatments of yarns and fabrics; and (v) pozzolan additions.

FRCM applications

Exterior cladding systems and facades are probably the most used employment in textile reinforced cementitious materials, through forms such as pre-cast panels, which appearance is a relevant criterion, besides high-finished surface quality, appropriate mechanical properties, freeform varieties, durability, and low environmental impact. Portland cement usually presents technical specifications of compressive strength up to 90 N/mm^2 and a modulus of rupture up to 10 N/mm^2 . Ventilated facade has element sizes that vary between thin ($0.5\text{--}3.0 \text{ m}^2$), medium ($4\text{--}7 \text{ m}^2$), and large ($12\text{--}18 \text{ m}^2$) (Papanicolaou, 2016). 2D textiles made of glass or carbon are commercially available to cladding systems and facades; nevertheless, other natural raw materials have been studied, for example, made by jute fabric (El Messiry et al., 2017). The Institute of Structural Concrete at RWTH Aachen University has a facade made of AR-glass fabric-reinforced concrete, it is coated by a thin concrete layer (4 mm) (Fig. 1a) (Fidelis et al., 2016) (Simonsson, 2017).

In this facade (Fig. 1a), the textile layer was positioned in the center of the cross-section. The panel was tested according to typical loads for façades (considering self-weight — 25 kN/m^3 , wind pressure, and wind suction). As a result, the authors reminded textile-reinforced concrete did not regulate yet in any standard at that time in Germany, although bending tests restrained initial crack, increased deformation

Fig. 1 **a** AR-glass reinforced concrete to the Institute of Structural Concrete façade at Institute of Structural Concrete (Simonsson, 2017). **b** Six shells for a pavilion in Kahla (Hegger et al., 2018)



capacity, and epoxy impregnation achieved the largest tensile stresses about 1400 MPa (Hegger et al., 2010).

Esthetic appearance and structural strength should be achieved when textile is applied to concrete shell; architectural forms mainly depend on bending load properties, which was previously done by steel structures. Replacement by textile materials has expanded, due to the promising of durability (without corrosion). Thus, most fabrics are impregnated by epoxy resin or rubbers (Hegger & Will, 2016), to improve their durability. An example of shell structure is the “Kahla Pavillon” (Fig. 1b), which is formed by triangular elements and can easily be disassembled. The shell is composed of an edge length of 5 m and thickness of 40 mm, while textile reinforcement is made by two layers of carbon fabric (3300 tex of yarn count). These forms are based on a conceptual design based on multiple shell elements than acting on biaxial load transfer, which minimizes transversal forces and increases durability, including these elements are applied to long-span buildings (Hegger et al., 2018).

Fabrics also have been applied as a solution for strengthening masonry, particularly in the case of seismic

resistance and historical monuments rehabilitation. They are used in external faces (Fig. 2) to bond them to mortar, which is made usually by glass, steel, carbon, or natural fibers (Dalalbashi et al., 2021). Many heritage structures were built without regard to seismic requirements and added fabric can include repairing the heterogeneity of masonry (Torres et al., 2021).

Masonry reinforced by textiles covers three main topics: first, basic behavior on mechanical properties, associated to strain ranges; second, load-bearing capacity on diagonal compression; third, capable of restoring the damage on masonry by textile materials (Fig. 2b). The last is related to repair of initial elastic stiffness and improvement of load-carrying capacity (Torres et al., 2021).

Finally, topics associated with intrinsic improvement of material (textile and cementitious) have been wide studies these topics related to avoiding degradation, interface fabric-matrix, mechanical properties, environmental exposition can be performed in also several applications (Ali-Boucetta et al., 2021; Graupner et al., 2020; Mercedes et al. 2018; Sadrolodabae et al., 2021; Syduzzaman et al., 2020).

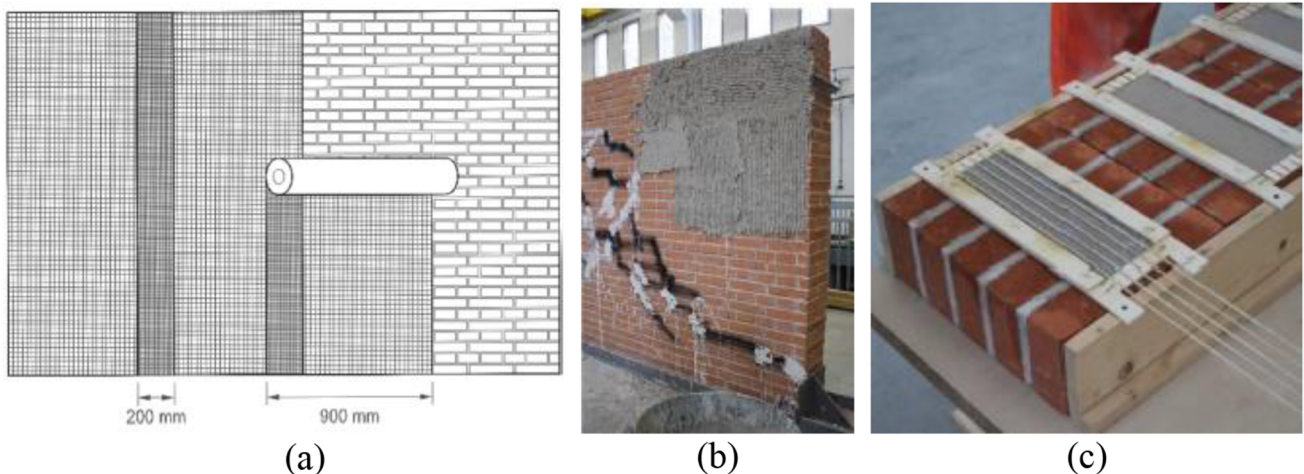


Fig. 2 Textile materials applied to reinforce masonry: **a** external cover (Torres et al., 2021), **b** repairing (Torres et al., 2021), **c** sisal yarns and cement (de Carvalho Bello et al. 2019)

Textile materials

Textile-reinforced composites have been employed in engineering applications, due to relatively low-cost (reduced manufacturing and processing cost), lightweight, replacing metals, and, in some cases, mechanical property enhancement (Ogin & Potluri, 2016).

Fiber geometry variation (perimeter, length, cross-section, and longitudinal) affects composite performance, mainly related to bonding properties between fiber matrix (Behdoui et al., 2013; Halvaei, 2021). Appropriated fiber length or aspect ratio influences the compressive strength of concrete. Fiber types as polymeric fibers may have low modulus and low strength, and therefore they do not much change composite strengths, but they aid in increasing ductility and reducing crack propagation; even high modulus/strength fibers can be used to structural materials (Halvaei, 2021).

Used methods for fiber processing are usually related to textile industry process; however, for composite applications, new materials have been developed, such as fibers and bundles are bonded by a chopped mat or continuous strand (Nijssen, 2015). Traditional textile materials are also applied to reinforcing composite: nonwovens, or tows or yarns, which are assembled into fabrics (wovens, braids, or knits) (Gowayed, 2014).

Intrinsic properties of cement material still require strengthening, due to brittleness, which means the propensity of crack propagation and shrink, as a consequence of drying of water from cement paste. Many types of fibers and textile materials including synthetic or natural sources have been employed to improve the brittleness of matrix, which allows an increase of strain capacity and often the tensile strength (Balea et al., 2021; Li et al., 2021).

Natural fibers

Fibers extracted from plants are composed of cellulose, lignin, pectin, and hemicellulose. The functions of these are as follows: cellulose is semi-crystalline and responsible for the hydrophilic feature; hemicellulose is amorphous polysaccharide and partially soluble in water; hemicellulose joins the cellulose forming microfibrils; lignin is hydrophobic and it is responsible for increasing the stiffness (Ali et al., 2018).

Tensile strength and modulus properties of cellulosic fibers are provided from cellular structure, which the responsible part is the middle layer of second wall; however, this still depends on higher degree of polymerization, amount of cellulosic, and lower microfibrillar angle (Abdul Khalil et al., 2017; Fang et al., 2020).

Many natural fibers have been employed for applications as reinforcement of composites. The most studied are sisal, coir, hemp, jute, and flax; in Table 1, these main produced cellulosic fibers are shown by type, origin, species, countries producer, and production (10^3 tons) (Lotfi et al., 2021).

Yarns

Cellulosic yarns are not so explored by researchers as compared with fabrics and other textile structures; however, knowing about them is important owing to their influence on material properties. Yarn features can be defined by type, twist, the influence of voids, moisture, and fiber volume fraction (Omrani et al., 2017).






In the textile industry, the linear mass or density is counted by the tex number that is the weight (in gram) per 1000 m and the twisted yarn is defined by twist direction (S-twist or Z-twist), depending on the level T ($T = \text{turns number per meter}$) and twist multiplier TM ($TM = T \sqrt{\text{tex}}$) (Scida et al., 2017).

The influence of interlacing yarns to tensile features, in general, is related to torsion angle, when yarn provides its near 20° , it provokes a decrease in longitudinal strength and modulus (Goutianos et al., 2006). Higher twist yarn can influence the reduction of yarn permeability, which causes appearance of void content and can influence the property decay (Omrani et al., 2017). Another reason for the decrease of composite properties is related to the misalignment of yarns, due to the outer part of it, which suffers less torsion than inside filaments (Scida et al., 2017).

The twist angle behavior can be seen most clearly in Fig. 3, in which the effect of hemp fiber bundle alignment reinforced polyethylene terephthalate (PET) matrix was measured. According to Fig. 3a, specimens with inclination angles of bundle fibers are shown and the tensile strength results are presented in Fig. 3b. The stress–strain curves demonstrate tensile performance is decreased at increased yarn twist angles. The maximum stress of the composites is assessed between the great range from 28 to 280 MPa (Madsen et al., 2007).

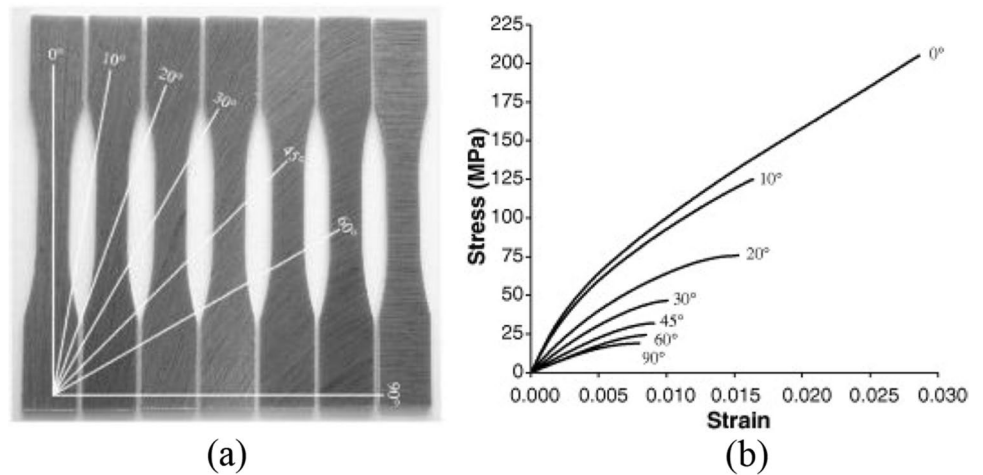
The difference between textile materials with and without entanglement can be seen in Fig. 4. These materials (Fig. 4) are made by hackled flax (24,000 tex, 0 twist, 0° of twist angle and 1.20 ± 0.6 MPa of tensile strength), roving flax (276 tex, 41 twists, 7.8° of twist angle and 59 ± 12 MPa of tensile strength) and yarn flax (78 tex, 280 twists, 19.4° of twist angle and 350 ± 65 MPa of tensile strength). When they were applied in epoxy matrix, results pointed out hackled flax had the highest mechanical properties (378 ± 2.6 MPa), followed by roving, in which achieved 20% higher stiffness and 25% strength (377 ± 24 MPa) than yarn (315 ± 46 MPa) (Baets et al., 2014).

Table 1 Annual natural fiber production of main cellulosic fibers applied to composites

	Fiber type	Origin	Species	Largest producer countries	World production (10 ³ tons)
	Coir	Fruit	<i>Cocos nucifera</i>	India, Vietnam, Sri Lanka	100
	Kenaf	Stem	<i>Hibiscus cannabinus</i>	India, Bangladesh, United States	970
	Flax	Stem	<i>Linum usitatissimum</i>	Canada, France, Belgium	830
	Bamboo	Stem	(>1250 species)	China, India, Indonesia	30,000
	Abaca	Leaf	<i>Musa textilis</i>	Philippines, Ecuador, Costa Rica	70
	Jute	Stem	<i>Corchorus capsularis</i>	India, Bangladesh	2500
	Sisal	Leaf	<i>Agave sisalana</i>	Tanzania, Brazil, Kenya	378
	Ramie	Stem	<i>Boehmeria nivea</i>	China, Brazil, Philippines	100
	Hemp	Stem	<i>Cannabis sativa</i>	China, France, Philippines	215
	Pineapple	Leaf	<i>Ananas comosus</i>	Philippines, Thailand, Indonesia	74

(Lotfi et al., 2021; Sanjay et al., 2016)

Fig. 3 **a** Tensile specimens of hemp/PET composites with the yarn axis inclined at various angles to the loading direction; **b** shows the corresponding stress–strain curves (Madsen et al., 2007)



Nevertheless, even though the studies have demonstrated good performance when roving or bundle fibers without entanglement are applied to composites, twisted yarns are the most employed yet, as it will be shown in **fabric ligaments**. One of reasons for choosing twisted

yarn is due to the process method, such as the main yarn impregnation is made by pultrusion (machine pull continuous yarn and cover it with a resin or mortar paste), which needs a minimum amount of entanglement or twist (Graupner et al., 2020).

Fig. 4 Three different flax fiber bundle types: on the left side — hackled flax (fiber aligned, width of about 25 cm, 30,000 tex); middle — flax roving (more stretched, but there is a low amount of twist, 280 tex); on the right side — flax yarn (twisted, 83.3 tex) (Baets et al., 2014)



Fabric ligaments

Fabric opening is related to the design pattern and count yarn (tex); this opening size is essential when it is employed at cementitious matrix opening can influence the cement insertion, which also depends on the viscosity of cement paste (El Messiry et al., 2017). According to Papanicolaou (2016), the grain size of cement should not get through more than 5 mm, which is considered a small grid size; another parameter also is presented in his research, to establish on parameter size, and it should be less than one third of the minimum mesh opening (Papanicolaou, 2016).

Cellulosic fabrics developed to reinforce cementitious composites are usually employed from woven technology, in which they are available on market from other applications with simple ligaments, such as plain and basketweave, in which it can be afforded in some researches (Cevallos & Olivito, 2015; Ferrara et al., 2019; Trochoutsou et al., 2021). For example, jute plain (388 g/m² of fabric weight, 922 tex) (Fig. 5a) and flax basket weave (375 g/m² of fabric weight, 353 tex) (Fig. 5b) were used

in various layers (one, two, or three) to reinforce cementitious matrix and then compared with glass fabric (320 g/m² of fabric weight, 593 tex), all samples presented better results with three sheets, except glass, that one sheet was used. Flax fabrics were stronger (5665.52 MPa of maximum load) and more ductile (21.7 mm of extension) than the sisal (4650.040 MPa of maximum load and 10.94 mm of extension), and glass stiffness achieved relatively high strength (2438.03 MPa of maximum load) and low strains (1.68 mm) (Cevallos & Olivito, 2015).

Besides the market products, fabric ligaments have been also applied and tested to composites. In this case, often fabrics are hand-made such as three types (Fig. 6) that were made with different openings, interweaving, yarns, and raw material (hemp — 0.034 g/cm², flax — 0.036 g/cm², sisal — 0.007 g/cm², and cotton — 0.054 g/cm²). Mercedes et al. (2018) also compared the mechanical properties of samples recovered by epoxy and polyester resins. Lastly, coated hemp FRCM reached the highest tensile strength (3481 MPa) and coated cotton FRCM made the greatest gain in strain capacity (18%). Resin coating increases the tensile strength and stiffness in all samples, in the case of hemp yarn achieved in

Fig. 5 a Jute plain-woven ligament (Cevallos & Olivito, 2015). b Flax basket woven ligament (Cevallos & Olivito, 2015)

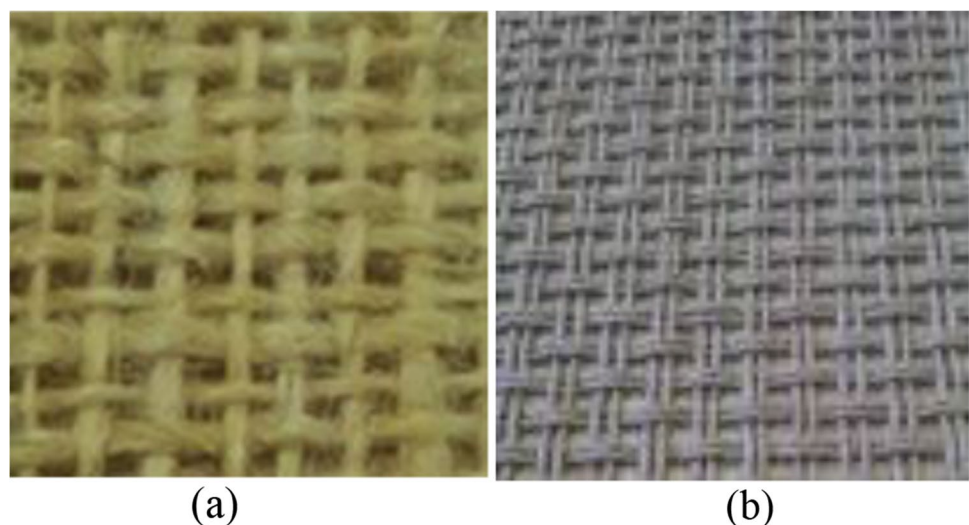
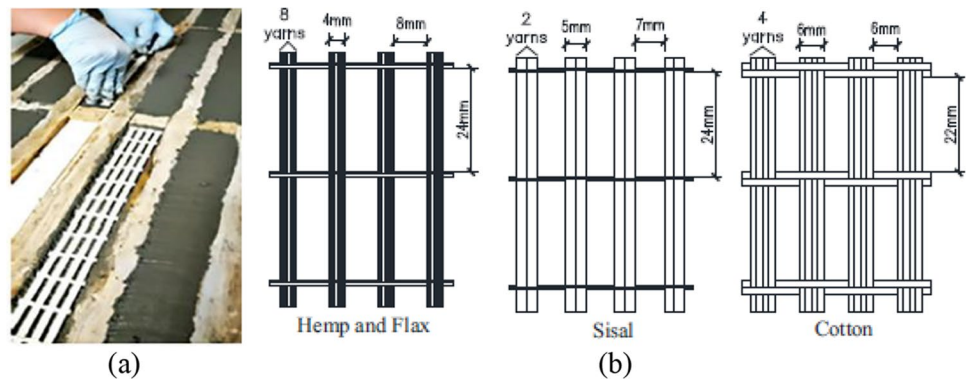


Fig. 6 a Hemp, flax, sisal, and cotton fabric (on the right, respectively) and ligaments used (on the left) (Mercedes et al. 2018)



tensile strength and modulus of elasticity increased by 84% and 92%, respectively. Epoxy resin has better compatibility with the mortar matrix than polyester (Mercedes et al. 2018).

Another research evaluated two matrices, first made by concrete and second, concrete plus metakaolin, in strengthening was utilized jute yarn (326 tex) and coated jute yarn (639 tex) by styrene-butadiene polymer to make a plain fabric, in which all samples were subjected to accelerated aging conditions (28, 56, 90, 180, and 365 days). Findings showed metakaolin composites reached expressively the highest values for pullout test at minimum exposition in 28 days and at maximum in 365 days of accelerated aging (0.48 kN and 0.40 kN, respectively), while only concrete matrix was the lowest (0.36 kN and 0.06 kN). In addition, coated yarn had a stronger bond than uncoated (Fidelis et al., 2016).

Nonwoven fabrics are another structure of reinforcement; four flax nonwovens were developed and compared to different thicknesses (2, 9, 12, and 14 mm) and weights (275, 680, 925, and 1200 g/m²) in multilayers (three or four); the best values were present by lower thickness (2 mm) and lower weight (275 g/m²) performed a higher penetration of the cement paste. Thus, this lighter nonwoven also was evaluated by entanglement of yarn (high and medium), with and without thermal treatment (hornification) and mechanical properties of composites (Claramunt et al., 2016). As result,

four layers of treated nonwoven and low thickness (1.2 ± 0.1 mm) with high needle punched presented high maximum tensile force (40.9 ± 16.1 N) and deformation ($48.0 \pm 6.7\%$) (Claramunt et al., 2017).

As mentioned before, some studies indicated that bundle fiber alignment presents the best performance as compared to yarns; thus, some studies have applied fabric developed by tapes, in which the fibers are bonded in longitudinal direction (scutched and hackled) (Fig. 3a) (Scida et al., 2017). Flax twill weave made from roving fibers and unidirectional fabric made of untwisted yarns (300 tex) were tested to reinforce epoxy composite into 10 layers; as resulted, yarn morphology had a low influence on composite performances, it is just the waviness ratios was all greater than 9 and the fiber volume fraction in the ply, as well as the areal weight decreases as the waviness ratio increases (Scida et al., 2017).

Fibrous 2D structure from nature form can be considered fabrics; Benaimeche et al. (2018) used date palm mesh (Fig. 7a) to reinforce cementitious matrix, and this natural mesh (mat) is composed of crossed irregular fibers (variation in the diameter), which it was tested with different volume fraction (2–10%), along with Portland mortar limestone and silica sand. The composite samples with 2% by volume presented similar values to literature data, which are made by conventional fibers; date palm composites achieved the

Fig. 7 Fibrous structure from nature ligaments: a date palm mesh (Benaimeche et al., 2018), b sponge gourd (*Luffa cylindrica* L.) (Querido et al., 2019)



peak load (average 2.016 kN) and flexural strength (average 5.671 MPa). However, date palm composite did not produce a positive effect on flexural strength and fracture toughness, associated with air incorporated at mixing phase and poor bonding with matrix (Benaimche et al., 2018). Sponge gourd is another structure made by nature, which vascular system forms are designed by a natural 3D fabric (Fig. 7b); Querido et al. (2019) characterized this plant by mechanical, morphological, and structural analysis, and the aspects were compatible with other cellulosic fibers. When sponge was applied (1 wt.%) to cement matrix and pozzolanic materials (metakaolin and fly ash), mechanical results of composite presented average flexural strength of 9.2 MPa (value is 50% better with sponge than without it) (Querido et al., 2019).

Pre-treatments of yarns and fabrics

Cellulosic FRCM presents a wide variety of opportunities, which it can depend on fiber origin and ligaments, such as it was presented before; however, it is necessary to ensure appropriate conditions to having adhesion fabric matrix, to avoid fiber degradation and guarantee the mechanical properties of composite and durability (Boulos et al., 2018; Syduzzaman et al., 2020).

The enhancement of mechanical properties on cellulosic FRCM is only possible if the adhesion between fiber/fabric and matrix is strong enough that it can be reached by reducing the hydrophilic capacity of cellulosic textile, through treatments (chemical, physical, or combined methods) (Page et al., 2021). Simultaneously, it is necessary to prevent cellulosic fiber degradation, an important factor that is provoked by alkaline byproducts (portlandite) contact, which is an element produced after chemical reactions by hydration process of cement process (Syduzzaman et al., 2020).

Ferrara et al. (2019) employed flax fabric without treatments to being exposed in environment media: first, protocol 1, verifying the mechanical properties in contact with water, marine, or alkaline; second, protocol 2, simulating the contact with hydraulic lime or cement mortars; third, protocol 3, simulating a long exposure time by accelerating aging method (flax fabric effects of hydraulic lime and cement on the mechanical behaviors). Results showed aging in protocol 1; the fabric was immersed in three media for 1000 h, and it did not lead to any significant decay; in protocol 2, after 7 days, the fabric decreased 16% of strength in hydraulic-lime and decreased 22% in cement mortars, but after 56 days, these valued did not change much more. And in protocol 3, a significant decrease occurred when the specimens were immersed for 55 days at a temperature of 55 °C, and there was a complete loss of strength (Ferrara et al., 2019).

To achieve better anchorage between cellulosic material and cement matrix, chemical and physical treatments are employed. Chemical treatment acts to eliminate non-cellulosic (hemicellulose and lignin) compounds in fibers, which increase the fibrillated surface and it can assist the bonding of OH elements to matrix, which in the most common chemical is alkali (NaOH) (Jiang et al., 2020; Sanchez-Echeverri et al., 2021). Other chemical processes can improve the adhesion though: coupling agent, such as silane or acrylic; esterification by acetylation. The physical methods change the surface morphology by utilizing mechanical forces in wet media and surface modification (plasma, steam blasting, hornification). Some of these methods are shown at Table 2; they are presented when are used to treat fabrics or yarns (Ballesteros et al., 2015; Li et al., 2021).

The swelling of fibers during the cement wetting process, followed by shrinking, is provoked by the curing process and drying of water and it can be manifested by a gap, affecting the adhesion between fiber matrix (Garikapati & Sadeghian, 2020; Page et al., 2021). For this reason, there are some treatments employed to reduce the water absorption capacity of cellulosic fabric, by thermal (hornification) or in another way combating the hydrophilicity by coating or impregnation process (El Messiry et al., 2017).

Coating meshes are a widely used commercial technique. In some cases, this prevents fiber degradation and improves the mechanical properties and the bond of the meshes with the matrix (Mercedes et al. 2018). In synthetic resin, epoxy is one of the most classes of thermoset, which cross-linking agents are amines and acid anhydrides that provide enhancing of mechanical properties and chemical resistance. Epoxy resin still has good compatibility with fibrous fillers applied to composites (Gibson, 2017). In addition, other resins are possible to recover the cellulosic textiles, such as the rubber styrene-butadiene (Fidelis et al., 2016), polyester resin (Mercedes et al. 2018), and linseed oil (Ali-Boucetta et al., 2021) (Table 2).

According to de Carvalho Bello et al. (2019), pure and impregnated (water-based adhesive) sisal yarns were embedded into a natural lime mortar to reinforce a masonry wall (Fig. 2c). They were tested by single lab shear and presented the maximum tensile strength at 169.5 MPa; this value was about 29% lower than yarns which were impregnated alone, evidencing uneven load distribution (de Carvalho Bello et al. 2019). Mercedes et al. (2018) evaluated inorganic resins (epoxy or polyester) on different fabric ligaments (Fig. 4c) and cellulosic materials (hemp, flax, sisal, and cotton); the results compared between these fibers were presented before (fabric ligaments), but specifically about the comparison of resin improvement, hemp fabric reached the highest mechanical properties and the difference of maximum load was 16.62% more to epoxy than polyester resin (Mercedes et al. 2018).

Table 2 Coating and treatments applied to cellulosic fabric to improve adhesion between fiber matrix; pozzolan additions and combined treatments

	Fiber	Type	Results	Authors
Coating	Jute fabric	Styrene-butadiene	Coated fabrics formed a stronger bond	(Fidelis et al., 2016)
	Jute fabric	Epoxy resin	High tensile strength and better bending performance	(El Messiry et al., 2017)
	Hemp, flax, sisal and cotton fabrics	Epoxy and polyester resin	Hemp reached strength (554.25 MPa, 92%) and cotton elongation	(Mercedes et al. 2018)
Physical treatment	2 jute fabrics (strip wrapped — 6 inch and fully wrapped)	Heat 50 °C — 48 h	Full wrap increased 40% of ultimate capacity and strip warp 25%	(Khan & Rahman, 2018)
	CO residue	NaOH	1% of cotton residue had an increment higher than 17% on its tensile strength	(Lima et al., 2019)
	PES/CO and flax nonwovens (3–7 sheets)	Hornification (dry–wet cycles)	6–7 presented better results, higher dimensional stability, and thus higher fiber–matrix adherence	(Sadrolodabae et al., 2021)
Pozzolan additions	Hemp fabric (8 sheets)	Nanoclay (1, 2, 3%)	Nanoclay (1%)	(Hakamy et al., 2014)
	Flax, sisal, and glass fabrics	Natural pozzolan	The flax fabrics were stronger and more ductile than the sisal fabrics	(Cevallos & Olivito, 2015)
	Sponge gourd	Metakaolin and fly ash	Low fraction of fibers (1%), 3D structure improves toughness	(Querido et al., 2019)
Combined treatments	Hemp fabric	NaOH/calcined nanoclay	Calcined nanoclay (1%) has great potential, but particles agglomeration affected the mechanical properties to improve the durability of treated hemp fabric	(Hakamy et al., 2015)
	Flax and sisal fabrics	NaOH/zirconia (ZrO ₂)	Improved durability treated fibers and the stronger adhesion	(Boulos et al., 2018)
	Date palm mesh	Boiling (5 min, 1, 2, and 3 h), NaOH, linseed oil coating	Alkaline treatment improves flexural strength at 28 days 60.1% more, boiling a slight improvement of 9% and linseed oil treatment does not contribute. Alkaline reduces the water absorption at 24 h by 8.9%, linseed oil by 69.8%	(Ali-Boucetta et al., 2021)

Pozzolan additions

Cementitious matrix aggressivity provokes cellulosic textile degradation, due to high alkalinity of cement (pH > 12) environment, which affects the mechanical and durability properties (Mercedes et al. 2018). The alkalinity of matrix is caused by chemical formation of hydrated products such as calcium hydroxide (portlandite) and calcium silicate hydrate, in which portlandite provokes the mineralization and degradation of cellulosic fibers, besides embrittlement of the fibers (Santos et al., 2021; Silva et al., 2017).

As previously mentioned, there are many options to treating and protecting the cellulosic fibers, to promote durability in cementitious composite. However, another way to avoid fiber decay is through the additions to matrix. These additions are named by pozzolans, in which act to transform high alkaline portlandite (Ca(OH)₂) to produce new reaction products; portlandite is the main byproduct from hydration which degraded the lumen of cellulosic fibers (Ardanuy et al., 2015; Teixeira et al., 2020).

Beyond the chemical reaction of portlandite, natural pozzolan has advantageous features to apply in the cement

industries, efficacious at minimizing the heat of hydration, acting as supplementary filler, besides low cost and accessible raw materials (Shukla et al., 2020). The major pozzolan additions are silica and alumina, beyond metakaolin, blast furnace slag calcined clay, or fly ash (Balea et al., 2021; Dembovska et al., 2017). The use of such pozzolan materials applied to fabric-reinforced cementitious matrix are presented in Table 2.

One of the important points in addition materials to matrix is adjusting the particle size for distribution, besides the accurately dosed amount, which are related to interfacial transition zone (ITZ) between particles in Portland cement paste with mineral compounds and cellulosic fibers must be measured and related to mechanical features of these composites (Correia et al., 2018).

Agricultural wastes have been highlighted as possible sources to convert them through the combustion process and foster pozzolanic activity. Straw, sugar cane, corn, and rice husk can be transformed to ash and provide pozzolanic powder by amorphous SO_2 . Great properties can be achieved using these agricultural wastes, which they can replace between 20 and 40% of cement mass, with the function of controlling the mortar expansion and also consuming $\text{Ca}(\text{OH})_2$ (De-Lima & Cordeiro, 2021; Hu et al., 2020; Kazmi et al., 2017). Another potential source of pozzolan is done by sewage sludge ash incineration (Zhou et al., 2020).

In summary, the present research findings of employment of cellulosic textile in FRCM highlighted the following points:

- Yarns: bundle fibers and low entangled yarns presented potential to increase the tensile properties. Some cases of cellulosic textile applications were performed in polymers. However, they have seldom been used in cementitious matrix.
- 2D fabrics: woven canvas (1×1) prevailed in cementitious composite applications. Besides the employment of natural fibers (hemp, flax, sisal, and cotton) showed good performances.
- Multilayer fabrics: 3 and 4 layers of fabrics presented better mechanical performance than few layer samples; it can be associated with an increase of maximum load and delay of the first crack in cement matrix (Halvaei, 2021).
- Textile-cement bonding treatments: one or more combined treatments have been employed for ensuring the bonding between textile-cement. The alkaline treatment (NaOH) is one of most employment to improve the adherence, in which it is used to modify the molecular structure (increasing surface roughness and crystallinity) (Li et al., 2021). On the other hand, even alkaline treatment is effective, it can be aggressive to surface of fibers (high concentration) and still generates toxic residues. Thus, other treatments and less harmful were applied to cellulosic textile in cementitious matrix (e.g., boiled, thermic, hornification).
- Cellulose degradation prevention: cellulosic textiles need to prevent degradation by alkaline elements from Portland cement matrix. In this regard, two ways have been chosen; first, resin coatings are applied to avoid contact with the cement; second, new chemical reactions are formed by pozzolans additions and these reduce the presence of portlandite. Epoxy is the resin coating most used, a thermoset polymer easier to manipulate and widely used in the same way in synthetic fibers; however, this resin also compromises interfacial bonding fabric matrix (Alatawna et al. 2021). Some sources of pozzolan additions were presented, such as from silica, metakaolin, nanoclay, and ashes from agricultural wastes; some of them, as metakaolin is considered expensive (Khatib et al. 2018), thus ashes from residues can be valuable and widely available (Hu et al., 2020).

Conclusion

Cellulosic fabric-reinforced cementitious matrix (FRCM) presents potential to wide uses, including structural and architectural applications. Nevertheless, the majority of studies are firstly focused on enhancing the intrinsic properties of materials, for later to perform the applications of these composite materials.

Physical properties of textile materials were discussed. Low entangled yarns present potential to increase the tensile properties. Some cases of cellulosic textile applications were performed in polymers. However, they have seldom been used in cementitious matrix. Simple design ligaments of cellulosic woven have been used to cementitious composites, mainly plains and basket waves, but also handmade fabrics from natural fibers (hemp, flax, sisal, and cotton) showed good performances.

Cellulosic textile structures for cementitious composites have employed one or more combined treatments, which presents the relevance of theme. There are many alternatives (chemical and physical) to cellulosic textile treatments (e.g., NaOH, thermic, hornification). Resin coatings and pozzolan additions increased the mechanical properties of composites when compared without these treatments.

Future investigations are necessary to improve cellulosic FRCM; opportunities for study in textile area are proposed: enlargement of fabric technologies, hybrid fibers in order to provide better performances, machinery technology (3D fabrics, complex knit) adaptation to use cellulosic fibers, and new architectural design for cellulosic FRCM applications (curved forms and sizes). There are still shortcomings in cellulosic fiber durability, which demands more studies.

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Data availability All data generated or analyzed during this study are included in this published article; more information is available with the corresponding author on reasonable request.

Declarations

Competing of interests The authors declare no competing interests.

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