State-of-the-art review of physical and mechanical properties of natural fibre-reinforced cementitious matrix composite

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Abstract:

In Viet Nam, natural fibre-reinforced cementitious matrix (N-FRCM) can be a material solution in some situations and works if research is oriented. This paper presents a state-of-the-art review of the physical and mechanical properties of N-FRCM composite. By inheriting previous review studies in the literature, this paper updates more on the experimental studies on the N-FRCM composite in the last decade. The review addresses, firstly the mechanical properties of constituent materials in N-FRCM as natural fibres, cementitious matrix, and natural fibre/cementitious matrix interface. Secondly, it addresses the physical and mechanical properties of N-FRCM composite, including the density, thermal and sound insulation, and compressive and tensile strengths. The paper then discusses the main factors that influence the properties of N-FRCM materials. Finally, the conclusion of this review terminates this paper.

Keywords: Physical; Mechanical behaviour; Natural fibre; Fibre-reinforced cementitious matrix (FRCM).

1. Introduction

In the last two decades, fiber-reinforced cementitious matrix (FRCM) composite is increasingly and widely studied and applied in infrastructure engineering as new elements or precast structures [1], [2]. However, the commonly used fibers are artificial fibers such as carbon fiber, glass fiber, polypropylene fiber, and PVA which have high strength and relatively high cost. These fibers are used in projects with specific characteristics that normal concrete cannot reach the required strength. In certain limited conditions, natural fibers can be a material solution for the development of infrastructure construction if they are carefully and methodically studied.

In the world, there were several studies focused on the natural fiber-reinforced cementitious matrix (N-FRCM) composite [3]-[5]. In these researches, the fibers used to reinforce the cementitious matrix are diverse such as jute fiber [6]-[8], flax fiber [9]-[12], sisal fiber [5], [13]-[16], coconut fiber [3], [10], [12],[17], [18], bagasse fiber [19]-[21], bamboo fibre [22], [23], etc. Almost these researches aimed to characterize the chemical, physical, and mechanical behaviour of N-FRCM composite, and to identify several of its properties as compressive strength, flexural tensile strength, chloride resistance, elevated temperature resistance, long-term durability in comparison with that of the original cementitious matrix. The effect of the parameters such as reinforcement ratio, length of short fiber, and fiber treatment was also highlighted. These researches have demonstrated the prospects for the use of N-FRCM in infrastructure construction.

In Vietnam, there were rare studies focused on the natural fibre-reinforced cementitious matrix (N-FRCM) composite [24], [25]. However, this material is not yet widely applied in the development of infrastructure construction. The reason is that this material has not been paid enough attention as well as the limitation in the transfer of the scientific research results to reality for local development. However, this material has good prospects for development in the future because in Viet Nam the agricultural and forest wastes as nature fibers still were not radically benefited. Furthermore, according to the economic-technical infrastructure development goals of the National Target Program on building new rural areas for the period 2021-2025 [26], it needs to use construction materials, especially cement-concrete with low cost, good strength, taking advantage of local resources as N-FRCM.

Aiming to develop several types of N-FRCM for infrastructure construction in Nghe An province, project T23-33 was performed with the support of the Hanoi University of Mining and Geology. A goal of this project is to contribute and improve additionally to the knowledge for a better understanding of N-FRCM materials. So, this paper presents a state-of-the-art review of its chemical, physical, and mechanical behaviour by inheriting previous review studies [27]-[30] and updating the experimental studies from 2018 to 2023. It begins by discussing the constitutive materials in N-FRCM such as a natural fibre, cementitious matrix, and textile/matrix interface. Then, available experimental studies on N-FRCM materials were reviewed and discussed on several aspects such as chemical and physical behaviour, mechanical behaviour and property, as well as the effect of several parameters.

2. Constitutive materials

The N-FRCM composite material includes natural fibre, cementitious matrix, and interface fibre/matrix. Each constitutive material has different characteristics depending on nature, utilization purpose, treatment method, etc. The science review points are highlighted in the sections below.

2.1. Natural fibre

Nature of fibre

As presented in the introduction section, the nature of used fibre is diverse such as jute fibre, flax fibre, sisal fibre, coconut fibre, bagasse fibre, banana fibre, hemp fibre, etc. Depending on the nature of fibre, they have different mechanical capacities. Table 1 presents the mechanical capacity of several most popular natural fibres researched and used in construction in comparison with E glass fibre.

Table 1. Property of several natural fibres in comparison with E glass fibre.

Fibre	Density (g/cm^3)	Young's Modulus (Gpa)	Strength (Mpa)	Strain (%)
Coir	1.2	4 – 6	150 – 175	15 – 40
Flax	1.53	43 – 72	900 – 1800	2.5 – 4.1
Jute	1.45	20 – 30	400 – 800	1.5 – 1.9
Sisal	1.40	9 – 21	610 – 720	3 – 7
Bagasse	1.56	50 – 80	500 – 1000	1.2 – 3.8
Hemp	1.07	35	390	1.6
E glass	2.54	72 - 73	2000 - 2400	3

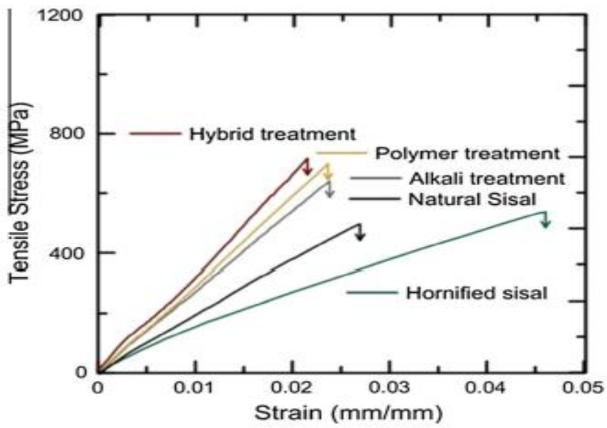
The physical and mechanical properties of several natural fibres as presented in table 1 were synthesized from the experimental results of different studies. From table 1, it could be found that flax fibre, after being treated in an extraction process, has the best mechanical performance among natural fibres, and less a little bit than E glass fibre. After that, the second and third ones in tensile strength are jute and sisal. That's why in Europe, these natural fibres have been produced as commercial produce (in mesh form) to manufacture composite materials (FRP or FRCM) using strengthening/reinforcing the existing structures (column, masonry, slab, etc) [31], [32]. In spite of not having good performance in comparison with other natural fibres, the coconut fibre (coir) was the most researched and applied fibre because of its availability, easy method to extract fibre product, and low price. So, coir FRCM composite has acceptable resistance for various applications in infrastructure construction. The presence of coir in FRCM has positive aspects by improving the ductility, tensile and flexural properties, and insulation properties of cementitious matrix [3]. However, with more coir fibre in the cement-based matrix, the workability of the matrix reduces, and the matrix porosity increases leading to a decrease in the load-carrying capacity of coir FRCM composite.

Fibre treatment

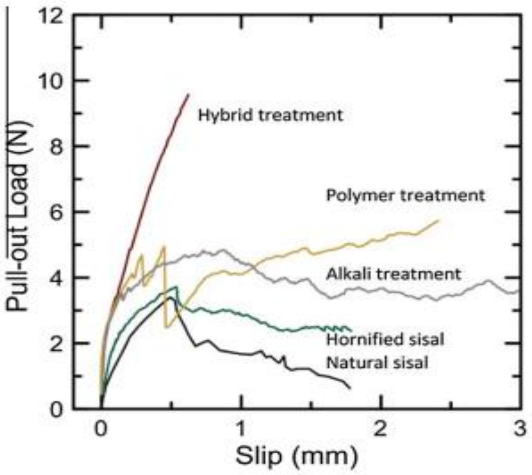
Almost natural fibres were treated by different methods before being used to manufacture the FRCM. This process aims to enhance its mechanical properties of itself as well as to improve the bond strength of the interface with the cementitious matrix. It could be named several treatment methods such as surface treatment method (physical or chemical method) [5], [20], [33], [34], hornification [5], [35], polymer impregnation [14], [16], [20], [36], or hybrid treatment [5], [37].

The surface treatment method enhances fibre-matrix interfacial adhesion to achieve a stronger bond strength. Ferreira et al. [5] have used alkali treatment with calcium hydroxide to treat the surface of sisal fibre in comparison with other treatment methods. As a result, low alkali concentrations (0.5–1%) have just removed the amorphous constituents, not really degrading the sisal fibre and thereby increasing its crystallinity. Thus, this treatment method improved the tensile strength and elastic modulus of sisal fibre as well as the interfacial adhesion with the cementitious matrix in the pure friction phase in comparison with untreated sisal fibre. Figure 1 presents the experimental results on the tensile strength of treated (with different methods) and untreated sisal fibres and the pull-out behaviour of the interface between corresponding natural fibres with cementitious matrix [5].

Hornification is a good method to treat the natural fibre by repeating several processes of humidity and temperature processing. This treatment process aims to promote a modification in fibre microstructure, resulting in dimensional stability [35]. The heating, drying, and cooling process performed on natural fibre must be slow to avoid possible thermal shock to the fibres. According to the results in [5], the hornification method hasn’t really changed mechanical properties of sisal fibre and bond strength with the cementitious matrix. However, a hybrid modification between hornification and polymer impregnation had a high positive on sisal fibre (see figure 1). Another solution for treating the natural fibre is polymer impregnation that solid content, density, viscosity, and pH of polymer liquid depend on the used polymer and type of natural fibre. Several types of polymers were generally used for natural fibre such as epoxy resin [22], styrene-butadiene [5], [22], [38], polyester resin [16], [22], [36], [39], castor oil reagent [20], [22], natural rubber latex [22], [40]. The modification by these polymer products helps natural fibre be strong and more stable in the cementitious matrix, as well as be well bonded to the cementitious matrix.



(a) Tensile behaviour of treated and untreated sisal fibres.



(b) Pull-out behaviour of interface between treated and untreated sisal fibres and cementitious matrix.

Figure 1. Effect of fibre treatment on mechanical behaviour of sisal fibre and fibre/matrix interface [5].

Natural fibre content

The natural fibre content in the mixture composition of FRCM depends on the goal of reinforcement by the natural fibres. In order to reduce the density or improve the physical property of FRCM composite for lightweight structure or thermal isolation applications, high content of natural fibre was added to the cementitious matrix. For example, the density of coir FRCM board could be as low as 0.25 g/cm3 when the ratio between cement and coir fibre in weight was 1:2. In this case study, the workability of the cementitious matrix was reduced because of the absorption of hydrophilic natural fibres from the cementitious matrix. In order to ensure the workability of FRCM (i.e., the flow value of the mixture was 16 ± 1 cm), it needs to add the high content of superplasticizer (maybe higher than 2-3 times than normal). For the goal of mechanical reinforcement, natural fibre addition was normally less than 5% of the cement weight. In order to identify an optimal value of this parameter for each type of natural fibre, parametric studies have been performed by varying fibre content in an accordant range. The choice of fibre content values for a parametric study depends on the length, cross section, and characteristics of natural fibres. Pedroso and Flores-Colen [41] have performed a statistical analysis from 55 experimental data sources on the influence of the natural fibre volume fraction and dimensions on the hardened-state density, compressive strength, and thermal conductivity of the cement-based composite. The analysis result highlighted the optimal range of the natural fibre content (by volume) fibre dimension for each composite property. For the hardened-state density, the highest increase (+5 to 10%, on average) was associated with content values between 0.10 and 0.50% (vol.) and dimensions between 5×10^{-5} and 1×10^{-3} mm. For the compressive strength performance, the increase (+5 to 30%, on average) was associated with quantities between 0.03% and 0.40% (vol.) and dimensions between 5×10^{-5} and 1×10^{-3} mm. For thermal conductivity, its highest values (+5 to 20%, on average) were associated with quantities between 0.03 and 0.40% (vol.) and dimensions around 1×10^{-4} mm. Veigas et al. [39] have investigated the effect of fibre percentage (from 0.8 to 2.6 %) on the mechanical properties (compressive, splitting tensile and flexural strengths) of uncoated and coated sisal fibre-reinforced cementitious composite. As a result, the mixtures with a fibre content of 2.0% by volume presented a better performance in flexural and tensile strength than other specimens, and thus, were selected for continuous studies. The reinforcement ratio of 2.0 % by volume of sisal fibre ranged from 1.2 to 1.5 for three types of specimens: uncoated, coated with polyester resin, and coated with shellac resin.

2.2. Cementitious matrix

The cementitious matrix used for N-FRCM composite is generally a matrix for cement-based composite. It is the product obtained after curing from the mixture of aggregates, cement binder, and necessary additives added with a reasonable amount of water. However, to adapt to the needs when combined with natural fibre, some requirements for the cementitious matrix must be satisfied as presented in the paragraphs below. The maximal diameter of aggregates for the cementitious matrix must be less than 2 mm. When Portland cement is used as a powder binder in the cementitious matrix, it generates an environment of high pH value, leading to the progressive degradation of natural fibre. In order to retardate this progress, it needs to reduce the pH value by using the pozzolana adjuvant as husk ash, blast furnace slag, silica fume, or fly ash to replace Portland cement. With the pozzolana in the cementitious matrix, the pozzolanic reaction occurs with calcium hydroxide and silica in the matrix, generating products of calcium hydrates (CSH or CAH) reducing the pH value and improving the mechanical property of the cementitious matrix. Therefore, it must have the right physical properties (especially workability) to fully penetrate the fiber-reinforced mesh to ensure the best surface adhesion between the two materials.

2.3. Interface fibre/matrix

The interface fibre/matrix is a constitutive part of composite material, which could enhance the mechanical capacity of the composite. In natural FRCM material, the bonding strength of the interface natural fibre/ cementitious matrix ensures effective working as well as good effort transmission between both materials. To identify the bond strength and mechanical behaviour of interface fibre/matrix, the pull-out test was generally used in the literature [42], [43]. As a result, the bonding strength of the interface natural fibre/cementitious matrix depended on different factors such as fibre treatment [44], [45], natural fibre characteristics [46], coating products [38], [44], etc.

Boulos et al. [45] have performed a comparative study on the durability of different condition of flax fabrics (untreated, pre-treated by acetone and alkali and ZrO_2-treated) in a cementitious matrix and the evolution of the fibre-cement matrix interface throughout 90 days of aging. The experimental result showed that the ZrO_2-treated specimens exhibited improved mechanical performance in the tensile strength of FRCM and bond strength with the cementitious matrix. The result of thermogravimetric and microstructural analyses showed that the presence of ZrO_2 nanoparticles in the interfacial transition zone (ITZ) acted as nucleation sites and accelerated the cement hydration reaction, improving the interfacial strength in comparison with untreated and pre-treated specimens. Ferreira et al. [46] have investigated the effect of natural fibre characteristics on the interface mechanics with cement-based matrices. Three types of natural fibres (sisal, curauá, and jute) were treated with a similar treatment process (washing treatment in hot water, drying, and then cutting), and then embedded in the cementitious matrix with different lengths (5, 10, and 25 mm). Figure 2 presents the typical pull-out behaviour of three natural fibres from the cementitious matrix block with different embedded lengths.

The capacity of the interface natural fibre/cementitious matrix was identified through the value of fracture energy (G_F) which could be determined from the bilinear bond-slip relationship for each type of specimen. The experimental results highlighted the superior performance of sisal fibres with the value of fracture energy (G_F) higher than 1.9 times and 3.5 times related to curauá and jute fibres, respectively. The SEM images of the sisal fibre interface with cementitious matrix showed the presence of finer particles of cement and pozzolanic addition creating the denser microstructure surrounding the sisal fibre and improving the mechanical capacity of the interface.

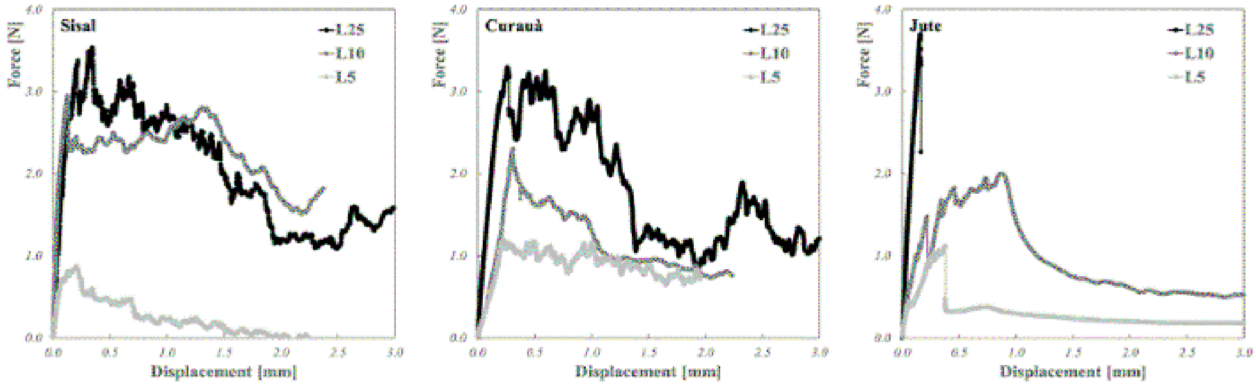


Figure 2. Typical pull-out behaviour of three natural fibres with the cementitious matrix [46].

Polymer impregnation is an effective method to improve the bonding strength of the interface natural fibre/cementitious matrix. The presence of polymer coating promotes higher amounts of hydration products around the natural fibres. The SEM images in [38], [44] have demonstrated the higher creation of cement matrix around the styrene-butadiene rubber (SBR) polymer treated-natural fibres. Figure 3 below presents a schematic model for fibre–polymer–cementitious matrix interfacial bonding, in which the main interaction between the SBR polymer and the cementitious matrix was due to Ca2+ ions. Furthermore, SEM results also showed the polymer anchor points in the cementitious matrix, leading to improve connection between both components. These reasons explain the improvement of bonding strength of the interface natural fibres/ cementitious matrix.

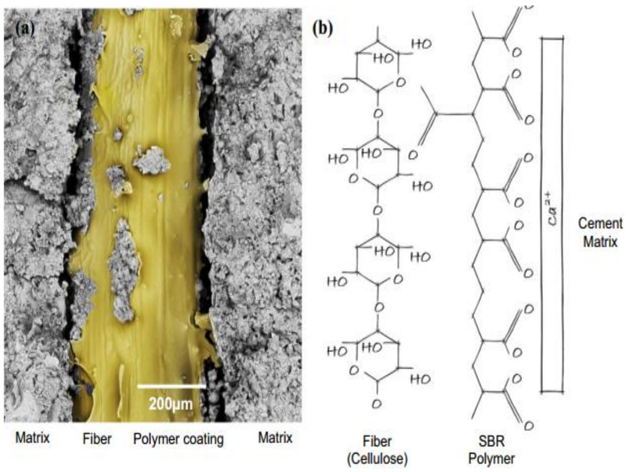


Figure 3. Effect of styrene-butadiene rubber polymer as natural fibre coating to improve the bonding strength with the cementitious matrix [46].

3. Physical and mechanical properties of natural fibre reinforced cementitious matrix

3.1. Physical properties

Density

The density of natural fibres is in the range of 1.05 – 1.6 g/cm^3, while that of fine-grained concrete is approximately 2.4 g/cm^3. Therefore, the addition of natural fibers in fine-grained concrete to fabricate N-FRCM can reduce the density of composite. According to the previous results, the addition of coir under 5% by weight of cement (i.e., normal coir content for structural applications) resulted in a reduction in the composite density by about 12%. Pedroso and Flores-Colen [41] reported the experimental results related to the relationship between the N-FRCM's density and the content by volume and size of natural fibers. The results showed that the fiber volume ratio significantly affects the density of N-FRCM. With the addition of natural fibres, the density of N-FRCM initially increases in the range of fibre content from 0.20% to 0.50% (by volume), and after that, it decreases (see figure 4). This evolution can also be drawn by the exponential regression equation: $y = e^{(-2.718x)}$ with R^2 = 0.8162. This equation allows us to approximatively predict the density of N-FRCM from the density of the original cementitious matrix and its natural fiber content. Figure 4 below shows the relationship between relative hardened-state density and natural fiber content (in % by volume) in N-FRCM.

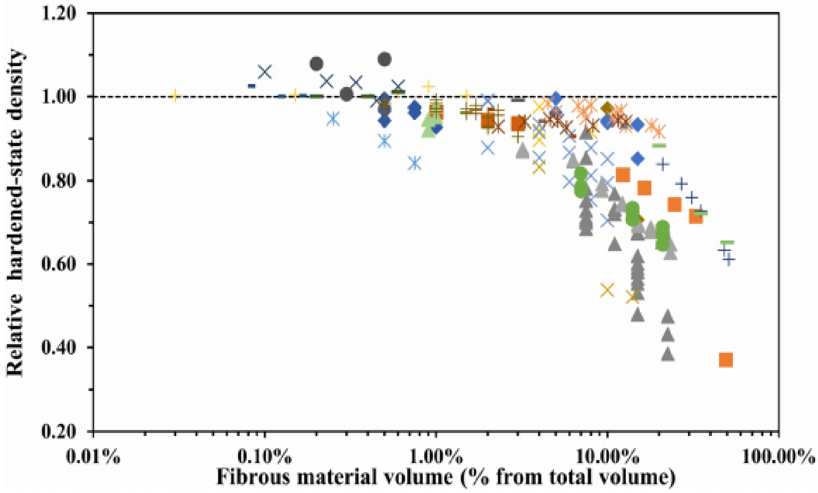


Figure 4. Effect of natural fibre content on the density of N-FRCM.

Thermal insulation

When manufacturing and using N-FRCM for thermal insulation purposes, coir fibre is a relatively popular choice. With a porous structure (porosity of about 21%–31%), it has relatively good thermal insulation properties [47]. Bui et al. [48] have studied the thermal conductivity of coir mats using a heat flow meter (HFM 436 Lambda equipment). The measured thermal conductivity ranged from 0.024 W/mK to 0.052 W/mK, which was equivalent to the design value of conventional insulation materials. The experimental results also showed that this insulation property of coir fibre was not affected by the fibre treatments by water and high temperature (immersion in boiling water for 2 h) or alkali corrosion (immersion in 5% NaOH for 30 minutes).

With coir FRCM, its thermal insulation is also relatively good, significantly improved compared to the cementitious matrix thanks to coir content. With the content of 5%, 10%, and 15% in weight of the cement binder, Lertwattanaruk et al. [49] showed a reduction in the thermal conductivity coefficient of 40%, 44%, and 46%, respectively for three fibre contents mentioned above. With a high coconut fibre content as a cement/ coir ratio of 1:2, the thermal conductivity could be ranged from 0.0547 to 0.1205 W/mK. This range of thermal conductivity is an upper threshold to consider an insulation material in standard [48], [50]. Previous experimental results showed that the thermal insulation capacity of N-FRCM was often inversely proportional to its compressive strength. This result is understandable because of the structure of the concrete and the volumetric weight of the material [41].

Sound isulation

Similar to the thermal insulation properties of N-FRCM, its sound insulation properties are also improved, related to the original cementitious matrix. Taban et al. [51] have investigated the sound absorption capacity of coir mats with a volumetric weight of 130 kg/m^3. The sound absorption coefficient was measured by an acoustic tube that was designed to identify a material's capacity to absorb sound. The better the soundproofing material provides the higher the sound absorption coefficient (closer to 1). The results showed that coir mats had a relatively low absorption coefficient at low frequencies and a significant increase in the sound absorption coefficient for higher frequencies. For example, sound absorption was 0.34 for a coir mat sample of 35 mm in thickness at a frequency of 1000 Hz while this coefficient was greater than 0.9 for a 25 mm in thickness at 2000 Hz. The thickness of the specimen had a significant effect on the sound absorption coefficient especially for low frequencies. Coir mats with thicknesses of 25 mm, 35 mm, and 45 mm have sound absorption coefficients of 0.11, 0.3,4, and 0.97 respectively at a frequency of 1000 Hz.

For sound insulation of N-FRCM, according to the experimental results of Olukunle et al. [52], the Db sound coefficient was reduced by about 5% in conventional mortar compared to the sound input, while for 0.25%, 0.5%, and 0.75% of coir additions, the reduction was 12%, 18,%, and 19%, respectively for three coir contents. It was also found that different ages of N-FRCM did not influence its sound absorption as mechanical properties. The sound insulation capacity of N-FRCM has not been studied comprehensively. So, it is necessary to conduct more studies on the sound insulation capacity of N-FRCM. If N-FRCM is comparable to other soundproofing materials, its application can be expanded further. The increasing use of natural fibers will push us one step closer to sustainability and global circularity [50].

3.2. Mechanical properties

The mechanical properties of N-FRCM were identified from compressive and flexural or tensile tests according to several standards. Depending on the maximum diameter of the aggregate and the size of the natural fibres used, the N-FRCM specimen was fabricated with the corresponding size. This section selects and synthesizes previous results for natural fibers commonly used in the world.

Compressive strength

Generally, the compressive strength of N-FRCM was not significantly improved related to the original cementitious matrix because the addition of natural fibres aims to enhance the tensile strength of the composite. On the contrary, in some cases studied, the presence of natural fibres had a negative effect on compressive properties, leading to a decrease in these values. The compressive strength of N-FRCM depended on several parameters such as the nature of the fibre, fibre content, fibre size, density, etc. The compressive strength of N-FRCM varied as a function of density. The statistical study of Pedroso and Flores-Colen [41] provided a logarithmic regression function to predict the relative compressive strength depending on the relative hardened-state density.

However, the experimental results are relatively scattered with the prediction model because the correlation coefficient R^2 = 0.65 is relatively misleading (see figure 5).

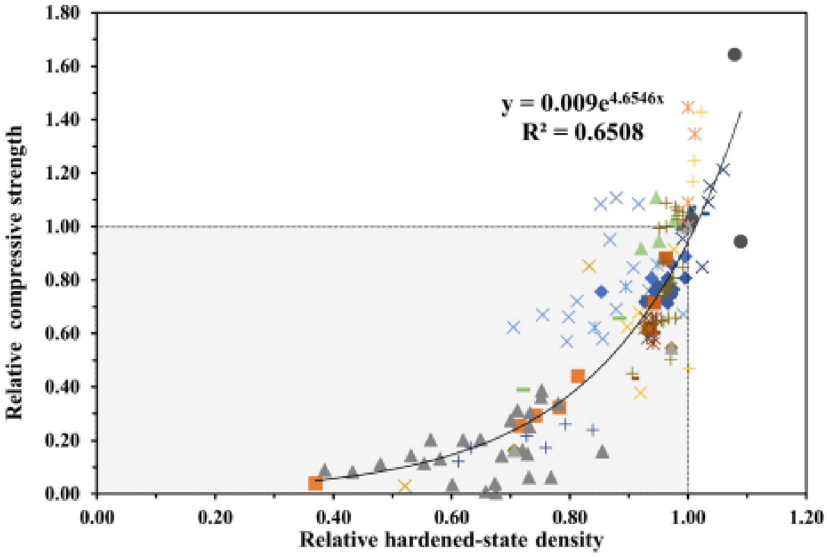


Figure 5. Correlation between the relative compressive strength and relative hardened-state density of N-FRCM [41].

When the fibre content increases beyond a critical limit value, the compressive strength of N-FRCM was in the decreased tendance. The experimental results of Candamano et al. [53] showed that with the addition of hemp fibres treated with acrylic rubber (fibre contents of

0.5%, 1%, and 1.5% by volume), the compression strength reduced respectively 8.1%, 1.3%, 16.2% compared to the original sample without natural fibres. Meanwhile, with similar content of untreated hemp fibre (0.5% and 1.5% by volume), the compressive strength decreased more, by 9.3% and 18.9%, respectively. The experimental results of Veigas et al [39] also showed a similar tendance of the compressive strength for sisal FRCM in the untreated and treated fibre cases with different resins and with different fibre contents (0.8%, 1.4%, and 2.0% by volume). Previous experimental studies showed that with a reasonable fibre content used, the compressive strength of N-FRCM could be significantly improved by up to 30% [41], [50]. With coir fibre, its optimum content in FRCM ranged from 1% to 5% by weight of cement. With other natural fibres, N-FRCM could reach an improvement in the compressive strength from 5 to 30% related to the original cementitious matrix. The effect of alkali or other pretreatment on the mechanical properties of coir FRCM was not noted in the literature. However, an appropriate pretreatment method should be carefully selected to improve the mechanical properties of N-FRCM. Fibre size affected greatly its mechanical efficiency in N-FRCM. Ali et al. [54] investigated the compressive strength of coir FRCM with different fibre lengths (25, 50, and 75 mm). With fibre lengths of 25 and 50 mm, there was no significant difference in compressive strength between both cases. The compressive strength of coir FRCM was improved by an average of 22%, 16%, and 12%, respectively for the fibre content of 1%, 2%, and 3%. For fibre length of 75 mm, compressive strength was improved only by 1% fibre content with an increase of 9%. With a fibre content of 2% and 3%, the compressive strength was reduced by about 6% and 10%. Large fibre lengths can be easily interwoven during concrete mixing, thereby reducing workability and increasing the porosity of N-FRCM. However, a short fibre length can lead to an insufficient embedded length for the bridging effect, the appropriate fibre length needs to be studied for practical application.

Table 2 below presents the experimental results on the mechanical properties of N-FRCM in previous studies. The values in Table 2 were selected to represent for the test series. These were the best positive results for the mechanical properties of N-FRCM.

Table 2. Several experimental results on mechanical properties of N-FRCM.

Authors	Fibre nature/ Treatment	Fibre content	Compressive strength (MPa)	Tensile strength (MPa)	Young's modulus (GPa)	Reinforcement ratio (%)
Veigas et al. [39]	Sisal fibre/polyester resin	2 % by volume	34.00	4.16	-	25.30
Castoldi et al. [39]	Sisal fibre/ Hornification 51mm	0.32 % by volume	-	3.59	-	4.10
Cadamano et al. [53]	Hemp fibre/ Hornification	1% by weight of cement	43.24	5.55	2.27	-1.35
Juradin et al. [55]	Hemp fibre/ 2.5% NaOH	0.34% by volume	61.40	7.60	-	10.20

Authors	Fibre nature/ Treatment	Fibre content	Compressive strength (MPa)	Tensile strength (MPa)	Young's modulus (GPa)	Reinforcement ratio (%)
Lima et al. [56]	Malva fibre/alkaline treatment	5% by weight of cement	7.00	4.10	-	17.20
Baruah and Talukdar. [57]	Coir fibre	1.5% by volume	25.10		4.07	17.00
Ali et al. [54]	Coir fibre	1% by weight of cement	43.20	4.25	37.8	13.30
Mannikadan et al. [58]	Coir fibre	2% by volume	41.10	4.75	-	90.00
Pederneiras et al. [59]	Coir fibre/ 15 mm	20% by volume	9.78	3.06	15.01	23.40

Tensile strength

The tensile strength of N-FRCM was identified from direct tensile, 3-point bending, and splitting tests. In general, the tensile strength of N-FRCM was improved compared to the original cementitious matrix thanks to the presence of natural fibres even with low fibre content [50]. Initially, without natural fibres, the cementitious matrix easily cracks and damages because of its weakness in tensile strength. With the reinforcement of natural fibres, the tensile load (direct tensile, flexural, or splitting force) is transferred to the fibres in the cementitious matrix by a fibre bridge effect. With the guaranteed bond strength between fibre and cementitious matrix, the tensile strength of N-FRCM can be improved even when there are more pores in the matrix. However, if too much fibre is added to the mix (as 5%, 10%, and 15% coir in the study of Lertwattanaruk et al. [49]), the additional surface area due to fibres is too large, leading to the decrease of the flexural strength because the bonding strength between the natural fibre and the cementitious matrix is not strong enough for the fibre bridge effect.

The direct tensile strength of N-FRCM is less commonly determined due to the more difficult experimental steps. Good technique is required to conduct tests and measure the tensile strength of composite specimens. Theoretically, as the strength of the fibre increases, the reinforcing effect of the fibre also increases because the fibre bridging effect makes the N-FRCM more resistant to tensile forces. Therefore, using fibre treatment methods (as mentioned and analyzed in section 2.1.2) to improve its strength was an efficient solution to reach a higher reinforcement ratio. However, fibre treatment did not always give a positive effect, depending on the natural fibre type, processing method, and treated materials. The experimental results of Veigas et al. [39] indicated that the reinforcing effect was not significantly increased with sisal FRCM when fibres were treated by surface coating with polyester resin and shellac resin. After 28 days, the tensile strength of uncoated sisal FRCM was 18%, 24%, and 24% higher than the tensile strength of the referent specimen (without fibre) respectively for fibre content of 0.8%, 1.4%, and 2.0%. For similar sisal fibre contents, the improvements obtained were 13%, 24%, and 25% for polyester resin-coated FRCM and 19%, 24%, and 20%, respectively for shellac resin-coated sisal FRCM. The experimental results of

Andiç-Çakir et al. [60] showed that the coir fibre pretreatment with 5% NaOH solution did not affect the flexural strength of FRCM. The average flexural strength of treated coir FRCM was 7.47 MPa while that of untreated specimen was 7.53 MPa.

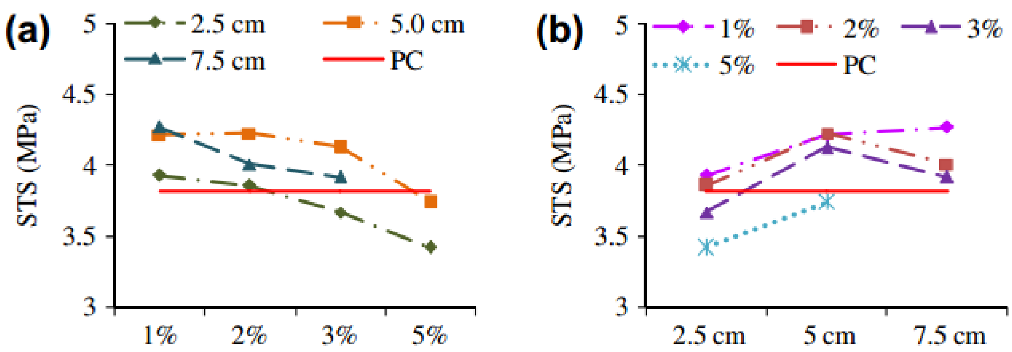


Figure 6. Effect of the coir fibre content and size on the splitting tensile strength of N-FRCM [54].

Another factor that also affected the reinforcement efficiency of the natural fibres was their length. Ali et al. [54] conducted the splitting tensile tests on coir FRCM samples with different fibre contents (from 0 to 5% by weight of cement) and fibre lengths (from 2.5 to 7.5 cm). Figure 6 a,b shows the effect of coir fibre content and length on splitting tensile strength (STS) of corresponding FRCM. The STS decreased with higher fibre content, however, it first increased and then decreased slightly with the increase in fibre length.

4. Conclusion

This paper presented a state-of-the-art review of the physical and mechanical properties of natural fibre-reinforced cementitious matrix (N-FRCM) to contribute additionally to the understanding of this material. Several conclusions could be drawn from this study:

N-FRCM is a suitable material for constructions that require not too high strength, however, could benefit all local materials and agricultural and forestry wastes. N-FRCM is suitable for technical infrastructure development programs.

Natural fibres could reach good strength with reasonable treatment. Conventional fibre treatment methods were alkali, hornification, use of powder products improving the bonding strength with the cementitious matrix, polymer coating, etc. Each treatment method had certain effects on the physical and mechanical properties of natural fibre. Therefore, depending on the type of natural fibre used, it needs to select the reasonable treatment method for the highest efficiency.

The bonding strength between natural fibres and the cementitious matrix was very important. Thanks to the guaranteed strength of this bond, the fibre bridge effect was formed, leading to a higher strength (especially tensile strength) of N-FRCM. The bonding strength was commonly identified from the pull-out test of natural fibres in the cementitious matrix block. The pull-out results depended on several factors such as fibre treatment methods, embedded length, fibre characteristics, environment, etc.

The physical and mechanical properties of N-FRCM were improved by the presence of natural fibres. Depending on the goal of fibre use, the designer used the type of fibre, fibre content, and fibre treatment method accordingly to reach the highest efficiency. The fibre length was also a factor affecting the mechanical properties of N-FRCM.

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