Materials Today Communications 35 (2023) 105833

Contents lists available at ScienceDirect

Materials Today Communications

journal homepage: www.elsevier.com/locate/mtcomm

Application of natural fibres in cement concrete: A critical review

Hussein M. Hamada [a,b], Jinyan Shi [c,*], Mohammed S. Al Jawahery [d], Ali Majdi [e], Salim T. Yousif [f], Gökhan Kaplan [g]

[a] Department of Civil Engineering, College of Engineering, American University of Sharjah, UAE
[b] Department of Construction Engineering and Projects Management, Al-Noor University College, Nineveh, Iraq
[c] Department of Civil Engineering, Central South University, Changsha, China
[d] Highways and Bridges Eng. Dept., Technical College of Eng., Duhok Polytechnic University, Duhok, Iraq
[e] Department of building and construction techniques, Al Mustaqbal University College, 51001 Hilla, Babylon, Iraq
[f] Civil engineering department, College of engineering, Nawroz University, Kurdistan, Iraq
[g] Atatürk University, Civil Engineering Department, 25240 Erzurum, Turkey

ARTICLE INFO

Keywords:
Cement
Natural fibre
Concrete
Mechanical properties
Sustainable

ABSTRACT

Sustainability of building materials is a growing concern, and the use of natural fibres (NFs) is one way to develop alternative low-cost renewable raw materials. The excellent performance of NF can be discovered in cement-based materials made by these fibres to reduce the warning of environmental threats. NFs play a crucial role in reinforcing the mechanical behavior of cement concrete, especially the tensile and flexural strengths. The important disadvantages of NF are relatively high moisture absorption and hydrophilic behavior, resulting to reduced bonding between the concrete matrix and fibres and thus effect the overall performance of concrete material. The use of physical and chemical treatments can enhance the aging resistance of NF in cement components due to a decrease in water absorption or an increase in surface roughness. Meanwhile, optimizing the binder components and curing regimes can reduce the alkalinity of the cement mixture, thereby delaying the degradation rate of NF. Due to the porous nature and weak interface of NF, it tends to increase the permeability of concrete materials and reduce their durability. Using NF to produce fabric or extract cellulose nanocrystal or cellulose nanofibre may be an effective enhancement method.

1. Introduction

Currently, concrete is the predominant building material, and it is widely used in the construction of infrastructure [1]. However, a large amount of natural resources are used and high pollution is generated in the concrete production process [2]. Concrete production not only consumes a lot of natural resources and energy, but also generates a lot of waste, especially carbon emissions [3]. Reusing industrial by-products and renewable materials is an effective way to improve the sustainability of concrete materials.

The main raw materials for producing concrete are binders, aggregates and water [1]. Currently, agricultural and industrial wastes are used to produce binders and aggregates to reduce consumption of natural resources [3]. To further improve the toughness of concrete materials, fibres are widely used and have high content in fibre-reinforced cement components [1–3]. Synthetic fibres are becoming more and more popular due to their enhanced effects on fatigue strength, tensile and flexural strengths, ductility, toughness, and impact resistance of concrete [4]. However, the carbon footprint and cost of synthetic fibres is higher, and the amount of waste fibres available is also lower. Therefore, natural fibres (NFs) become an effective replacement for synthetic fibres with lower cost and environmental impact.

The NF like abbaca, kenaf, bamboo, jute, bagasse, date palm fibre, pineapple leaf fibre, etc. are applied to reinforce the cement composites owing to their properties such as a cost-effectiveness, a wide range of mechanical, sustainability, ease of availability, biodegradability, thermal, and physical properties [5]. In cement-based materials, NFs have a positive effect on improving their fracture behavior. Gao et al., also found that adding 2% sisal fibre (18 mm) to ultra-high performance concrete (UHPC) increased the flexural strength of the sample by 16.7% [6]. Meanwhile, NF is also used as functional components in cement-based materials, such as internal curing agents and carriers of bacterial spores. Jongvisuttisun et al. improved the volume stability of cement components using pulp fibre as an internal curing agent [7].

* Corresponding author.
E-mail address: jinyan.shi@csu.edu.cn (J. Shi).

https://doi.org/10.1016/j.mtcomm.2023.105833
Received 20 January 2023; Received in revised form 18 February 2023; Accepted 15 March 2023
Available online 17 March 2023

However, some of the issues such as poor moisture resistance, lower melting point, and weak interfacial adhesion make the NF fewer motivation. Treatment of NF surface might improve the interfacial adhesion between NF and cement matrix, and it can enhance the surface roughness and moisture resistance of NFs [8]. Li et al. found that the toughness of the fibre-reinforced cement components with alkali-treated NF was improved due to the enhanced bonding properties between the fibres and the matrix [9]. Therefore, the performance improvement of cement concrete can be achieved by optimizing the content/type of NF and strengthening its properties.

This paper presents a systematic review of the properties of NF-reinforced cement components and an outlook for future research. First, NFs for cement components are reviewed, including their physical, chemical and mechanical properties. Then, the effects of NF on the mechanical properties, durability and microstructure of cement-based materials are discussed. Meanwhile, measures to further enhance the properties of NF-reinforced cement components are proposed. Finally, the application and environmental benefits of NF-reinforced cement components are discussed.

2. Characteristics of NF

2.1. Chemical composition of NF

Usually, all plants comprise lignin, cellulose, and hemicellulose which contains the three main organic components. Furthermore, NF likewise comprise water-soluble substances, waxes and pectin [10]. The chemical composition of fibre in the same plant is different, which is affected by the plant growing environment, fibre extraction method and geographical factors [10].

The fibres properties are influenced by the arrangement inside the cell wall and the micro fibril angle [11]. Table 1 presents the chemical composition of NF investigated by the previous studies. The cellulose content is the most component among other components, and upsurges from main layer to inferior layer, whereas hemicellulose amount stays similar for each layer, however lignin amount is mutual with cellulose trend. The secondary layer is responsible to the mechanical and physical properties of NFs. Moreover, the lower micro-febrile angle and higher content of cellulose lead to increase the strength values [12,13]. According to Table 1, there are difference among the similar types of NF on the chemical constituent abridged from the literature.

NF with comparatively high content of cellulose comprise kapok, ramie, cotton, and cotton linter. Fundamentally, the lowest lignin and high cellulose content leads to higher tensile strength. Nevertheless, there are many factors effected on the tensile strength and association with linear development. The cellulose structure, lignin, and hemicellulose [36]. The cellulose content is according to the species and age of the plant. Cellulosic in NF have poor dimensional stability and large capacity of moisture absorption because of typically swell in interaction with water [37]. Connection between material matrix and fibres with NF may be influenced by both the hydrophilicity and hydrophobicity of fibre [5]. The degradability and properties of NF are effected by diverse

Table 1
Chemical composition of NF.

Fibre type	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Ash (%)	Wax (%)	Ref.
Cyperus pangorei	68.5		17.88	3.56	0.17	[14]
Kenaf fibres	56.81	13.59	18.27	7.87		[15]
Cortaderia selloana Grass	53.7	14.43	10.32	4.2	3.1	[16]
Congon grass	34.23	36.23	26.99			[17]
Sabai		24	22	6		[18]
Esparto	33–38	27–32	17–19	6–8		[18]
Bamboo	26–73.83	12.49–31	10.15–36.88	1.7–5		[18–20]
Sugar	32–48	27–32	19–24	1.5–5		[18]
Momordica charantia	61.2	17.3	4.8	2.24	1.1	[21]
Sida mysorensis	53.36	15.23	9.46	3.33	0.86	[22]
Citrullus lanatus	53.7	12.5	10.1	2.17	3.2	[23]
Rye	33–50	27–30	16–19	2–5		[18]
Ost	31–48	27–38	16–19	6–8		[18]
Barley	31–45	24–29	14–15	5–7		[18]
Wheat	29–51	15–32	16–21	4.5–9		[18,19,24]
Rice	28–57	23–33	12–19	15–20	8–38	[18,19,24]
Phragmites communis	44–46	20	22–24	3		[18]
Seed flax	43–47	24–26	21–23	5		[18,25]
Fibre flax	71	18.6–20.6	2.2		1.5	[19,23,24,26–28]
Kenaf	31–57	20.3–33.9	9–21.2	2–5		[18,29]
Jute	45–71.6	13.6–21	21–26	0.5–2	0.5	[18,19,21,24–27,30]
Hemp	57–77	14–22.4	3.7–13	0.8	0.8	[18,19,21,23–27,39]
Ramie	68.6–91	5–16.7	0.6–0.7		0.3	[19,24,26,27]
Sun Hemp	41–48	8.3–13	22.7			[29]
Banana	60–65	19	5–10			[29]
Bagasse	55.2	16.8	25.3	-	-	[17,19,24,26]
Kenaf	37–49	18–24	15–21	2–4		[25,30]
Sorghum bagasse	42.36	30.67	24.98			[20]
Jute	41–48	18–24	21–24	0.8		[18,25,30]
Abaca	56–63	15–25	7–9	3	3	[18,19,24,26,27,29]
Sisal	47–78	10–24	7–11	0.6–1	2	[18,19,24–27,29,30]
Curaua	73.6	9.9	7.5			[19,24,26,27]
Pineapple	81		12.7			[19,24,26,27]
Henequen	77.6	4–8	13.1			[25,31]
Cotton	82.7–90	5.7			0.6	[19,24,26,27]
Cotton linter	99–95	1–3	0.7–1.6	0.8–2		[18]
Water Hyacinth	65.07	15.07	11.38			[32]
Sansevieria	79.7	10.15	10.13	1.4	0.86	[33]
Agave americana C. fibre	68.54	18.41	6.08	3.29		[34]
Areca palm leaf stalk	57.49	18.34	7.27	0.71		[35]
Coir	32–43	0.15–0.25	40–45			[19,24,26,27]
Kapok	64	23				[19,24,26,27]

cell wall polymers of lingo-cellulosic material [38]. Furthermore, cellulose has influence on the strength of NF, whereas lignin increases the char formation and UV degradation. Based on Table 1, Gu et al., [39,40] reported that the coir fibre has the highest content of lignin. Coir has lower content of hemicellulose and cellulose with micro-febrile angle that influence the plant properties which comprise resilience, strength, wear, damping, high elongation at break, and resistance to weathering [41].

2.2. Physical and mechanical properties of NF

The performance of fibre-reinforced concrete (FRC) is closely related to the physical and mechanical properties of NF. In general, NF plays a role in toughening and internal curing in cement mixtures, which is determined by the properties of NF. In general, NFs have longer lengths and are cut to the proper length for use. Meanwhile, NF has a thinner diameter and a density around 1 kg/m^3, as shown in Table 2. The tensile strength of NF cannot be ignored, which determines its toughening effect in cement-based materials. Due to the unique microstructure, it tends to have the ability to absorb water, and it will swell during the water absorption process (See Fig. 1) [42].

3. Types of NF used in cement concrete

The NF have been obtained from nature and classified by the fibre source. It can be resulting from minerals (asbestos), plants, and animals (hair, wool, silk). The most utilized of these NF in reinforcement composites are plant fibres [53,54]. The NF produced from the plant such as grass, wood, fruit, leaf, seed, stalks, and bast [45]. Last studies on NF composite showed that a certain characteristic of fibres is similar to the fibres-reinforced composites. These fibres composites, in the form of sandwich plates, tubes, and panels are used to substitute wooden fitting, and matches, for noise insulating panels and furniture [55,56]. The NF are classified for different types as illustrated in Fig. 2 [53].

The NF are utilized to reinforce concrete mixtures and can be changed into diverse forms, like fabrics, yarns, rovings, and mats [57]. Up to the present time, numerous industrial techniques are explored to produce composites, like pultrusion, injection molding, film stacking, resin transfer molding, manual winding, vacuum infusion, compression molding, hand lay-up, and filament winding [58,59]. Whereas choosing a certain industrial technique, different reasons essential to be measured, including economics involved in the process, shape and size of the composite, and properties of raw material [55,60]. The NF are categorized into three main categories as classifies by the previous studies, namely cellulose/lignocellulose fibres, animal fibres, and mineral fibres [61].

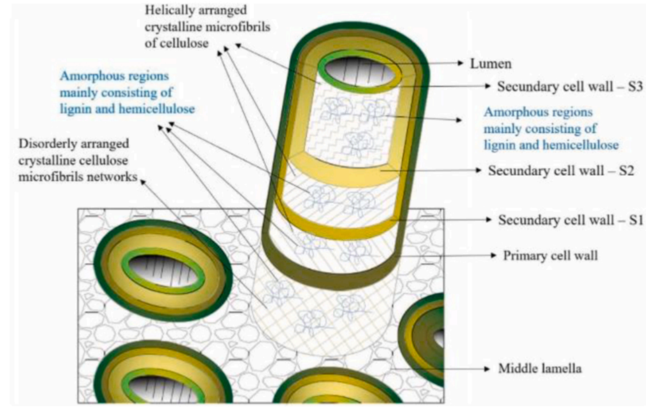

Fig. 1. The typical structure of NF, reproduced under license number 5490820745414 from [42].

3.1. Flax fibres

Flax fibres has been used by Xu et al., [62] to study the feasibility of nano-crystalline cellulose production. They treated these fibres types by washing and distilled H_2O, then drying at 70 ℃ for 1 d in air oven, after that the fibres were ground by grinding mills. The resulting fibres were in powder form. In general, there are many pretreatment methods to treat these fibres such as ultrasound pretreatment, chemical pretreatment, and microwave pretreatment [63]. The mechanical properties of small fibres indestructible blends are better due to increase the ↱soaking measurement. The tensile strength of the reinforced matrix with fibres enhances with the fibres content increase. Goudenhooft et al. [64] studied ability of flax fibres to save their strengths though showing structural differences. The mechanical properties have been improved of flax fibres was similar to the glass fibres. Moreover, Page et al. [49] investigated the compressive and flexure strengths of flax fibres in concrete in both hardened and fresh stages. Table 3 show the effect of flax fibres on the strength of concrete.

3.2. Hemp fibre

Hemp fibres are considered to be an outstanding substitute for reinforcing composite ↱materials. Weak internal adhesion between high density polyethylene pattern and hemp fibre and ↱fibre tensile fracture,

Table 2
Physical and mechanical properties of NF.

Ref.	NF	Length (mm)	Diameter (mm)	Density (kg/m^3)	Tensilestrength (MPa)	Moisture content (%)	Young modulus (GPa)	Elongationat break (%)	Water absorption (%)
Majumder et al., [43]	jute fibres				53.27	42		1.4	1.83–2.5
Islam and Ahmed [44]	Jute fibres	10–20	0.10	1.45	480				1.6
Faruk et al., [45]	Abaca			1.5	400		12		
Alam et al., [46]	Kenaf fibre	300		1.04	146	4.42	14.55		0.0961
Grubeša et al., [47]	Hemp fibre	18	0.50		63.6			3.0	
Peña-Pichardo et al., [48]	Cotton fibre			1.5–1.6	287–597		5.5–12.6	7.0–8.0	
Page et al., [49]	flax fibres	12, 24 or 36	0.0146	1.521	1254		65.5		1.324
da Gloria et al., [50]	Sisal fibre	60			447		19		
Ramesh [51]	Hemp	50–500		1.2	270–900		4.8	1–3.5	10–14
Banthia et al., [52]	Cellulose	2.3	0.016	1.1	300		35		

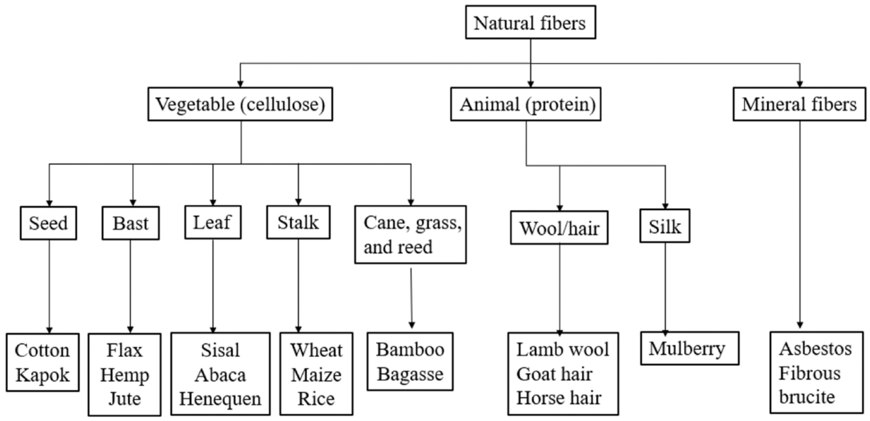

Fig. 2. Classification of NF, reproduced under license number 5491190706056 from [53].

also flexural strength of hemp fibre resistant composites and fibre delamination ↱were detected to be the main reason for the reducing splitting tensile strength ↱[72]. Lu et al. [73] investigated the chemical handling of hemp fibres from diverse techniques. They qualified that fungal retting resulted to a slight decrease in force from the lower part to ↱the upper part as well improved mixtures properties. Sawpan et al. treated hemp fibres using acetic anhydride, sodium hydroxide, silane, and maleic anhydride, and found that the average Young's modulus of the treated fibres was increased, and the average tensile strength of the sodium hydroxide-treated NF was also improved compared with the control group [74]. Poletanovic et al., [75] investigated the effect of hemp fibre with a diameter of 8–60 mm. They concluded that the density of mortar reduced by up to 5% regardless of the fibre content and water absorption increased by about 20% for 1% fibre content. Overall, numerous studied investigated effect of hemp fibres on the concrete properties, as shown in Table 4 [76].

3.3. *Jute fibre*

Jute is one of the bast fibres scientifically famous. The external side and inside stem of the stem are separated, and the fibres is the external part which separated ↱alone automatically. Milky and Abdul-Jabbar [82] investigated the natural jute fibre without treatment and associated with numerous treated these fibres. They revealed that a high creep occurred the in raw composites at elevated temperatures. Also, Majumder et al., [43] adopted the jute fibres to enhance the performance of concrete and show that the jute fibre is mostly having a golden shine, with a main diameter of around 0.08 mm and a length of 3–4 m, and has a golden color [44]. Table 5 show the effect of jute fibres on the concrete properties.

3.4. *Kenaf fibre*

Kenaf fibre is an industrialized crop and developed as a significant plant sophisticated ↱in developed countries. It has an outstanding ability to reinforce ↱composite material owing to its tremendous properties like mechanical strength and low density ↱ [90,91]. Kenaf is a warm-season yearly mostly refined in soft bast fibre in its stem. It goes to the Malvaceae family and it is similar to okra and cotton, a family remarkable for both its horticulture and economic significance. It raises in an extensive scope of climate situations. The diverse growth factors affect the properties of kenaf fibre. Enzymatic retting or chemicals can separate the stem simply [92]. Kenaf plant can be absorbed the phosphorus and nitrogen in the soil and they assistance upsurge the fibre yield, stem diameter, crop height, and cumulative weed weight [93].

The high performance of kenaf fibres made it a perfect component to be incorporate as a strengthening material. The hydrophilic possessions can be measured by treating of fibre surface with NaOH [94]. The concrete samples reinforcement by kenaf fibre showed ductile failure comparing with the brittle failure of plain concrete. The use of un-treated kenaf fibres in concrete led to increase the workability of concrete [95]. Elsaid et al. [96] stated that the usage of kenaf fibres in concrete led to increase the compressive, flexural and tensile strengths compared to that concrete without addition these fibres. Kim et al. [97] reported that the improvement could be observed in the compressive and flexural strengths of concrete comprising kenaf fibres with acrylamide over gamma-ray radiation. Mohsin et al. [98] reported that the kenaf fibre had a significant effect in decrease the crack propagation through increasing the flexural strength and enhancing the ductility. The use of kenaf fibres by 0.25–0.5% led to a considerable decreasing in the drying shrinkage and autogenous shrinkage of cement paste [99]. Table 6 shows the effect of kenaf fibres on the concrete properties.

4. Influence of NF on concrete properties

4.1. *Mechanical properties*

The mechanical properties are mainly affected by the nature of materials components in the concrete mixtures. For instance, the addition of NF on the concrete mixtures will leads to change the mechanical properties depending on the properties of NFs. In general, NF has a positive effect on improving the flexural properties and toughness of cement concrete. Meanwhile, the internal curing effect of NF is also beneficial to the improvement of compressive strength.

4.1.1. *Compressive strength*

The mechanical performance of the FRC is effected by numerous factors, including the shape and size of fibres and the fibre content in the FRC. The compressive strength is the main factor that evaluates the performance of concrete used in the construction projects. Concrete structures with high compressive strength value has ability to bear higher pressure than that weak concrete [104]. The fibre content has a significant effect on the gaining a compressive strength in foamed concrete. Most of the studies concluded that the use of 0.5% of NF was the optimum volume to achieve higher compressive strength of RFC [105, 106]. While, other researchers reported that the use of 1% NF was the optimum content to achieve the highest compressive strength of RFC [107,108]. Other study revealed that the mechanical performance of FRC using kenaf fibre had better performance than that of ordinary concretes [109]. It was reported that the addition of 1.5% coconut fibres led to enhance the compressive strength of FRC by 25% compared to control concrete (See Fig. 3) [110]. The compressive strength of FRC made of sisal, jute, bagasse, sugarcane, and coconut fibres improved up to 2%. Extra addition of NF (beyond 2%) led to reduce the compressive strength. The use of 0.5% of sisal and jute fibres resulted to increase the compressive strength from 11.6% to 20.2% compared to normal

Table 3
Effect of flax fibres on the mechanical properties of cement concrete.

References	Flax fibres (vol%)	Effect on the concrete properties
Page et al. [65]	0, 1%, 2%, and 3%	Addition the flax fibres led to enhance physical properties of mortars, it absorbed a huge quantity of water, and reduced the compressive strength with increasing fibre content. While, the optimum fibre content was 1.0–2.0% (vol.), it got higher flexural strength. As well as enhanced the properties of thermal insulations of mortar.
Kouta et al., [66]	0, 0.3%, and 0.6%	The use of flax fibres resulted to improve concrete ductility owing to the bridging effect and load distribution of fibres. Increasing the fibre length and flax fibre content increased the breaking energy and tensile strength of the samples.
Rahimi et al., [67]	0.3%, 0.6%, 0.9%, 1.2%, 1.5%, and 1.8%	The incorporation of the flax fibres had an important effect on the improving the flowability, mechanical and rheological properties of the cement composites. The use of 1.8% alkali-treated flax fibres led to delay the setting times by 5 h comparing with the normal mixture without fibres.
Zhang et al., [68]	0, 2%, 4%, and 6%	Incorporation of flax fibres and steel fibres led to reduce spalling of UHPC, in both cased low and high fibres content. Nevertheless, very high volume of flax and steel fibres might negatively effect on the resistance of spalling. Also, the flax fibres might cause to reduce the compressive strength, whereas the compressive strength increased when used the steel fibres.
Kouta et al., [69]	0%, 0.3% and 0.6%	Addition flax fibres to the concrete mixture led to increase the 28-d compressive strength of concrete and improve the ductility. Also, increase percentages of flax fibres led to decrease the cracking risks and plastic shrinkage of concrete.
Page et al., [49]	0.1%, 0.2%, and 0.3%	The use of flax fibres had a significant impact in decreasing the workability of concrete due to high specific surface area and water absorption. While, the flexural strength increased and compressive strength decreased due to increase of the fibre content in the concrete.
Rahimi et al., [70]	0.75%, 1.5%, and 2.5%	Addition of treated flax fibres to the concrete resulted to increase the compressive strength up to 12%, after minimizing the fibre impurities, like waxes, pectin, and lignin. Also, addition flax fibres improved the flexural strength of concrete. The splitting tensile of concrete increased by 16% due to use treated flax fibres.
Page et al., [71]	0.1%	The use of flax fibres in the concrete with different binder had lower effect on the early-ages compressive strength than that of fibre-reinforced mortar produced by 100% OPC. Similarly, the flexural strength was increased with incorporating flax fibres and OPC as a main binder material.

Table 4
Effect the hemp fibres on the concrete properties.

References	Hemp fibres (vol%)	Effect on the concrete properties
Poletanovic et al., [77]	1%	The addition of hemp fibre treated by the NaOH led to separate the fibres. The addition of treated fibres into the concrete increased the compressive strength by 24% and flexural strength for 19% in the case of wet cycle, while the compressive strength increased by 43% and flexural strength by 23% in the case of dry cycle. Reducing porosity was the main cause for improving the mechanical properties of concrete. The surface of hemp fibres treated with 6% NaOH had the highest compressive and flexural strengths.
Gencel et al., [78]	0.75%, 1.5% and 3%	Increasing the fibre content in the concrete led to increase the slump and thus improved the workability of concrete. Also, increasing the fibre content led to increase the long-term compressive and flexural strengths. Incorporating 3% hump fibres decreased the sorptivity coefficient up to 23.15% compared with plain concrete.
Sáez-P é rez et al., [79]	0.3% and 0.6%	Addition of wet hemp fibres enhanced the behavior of the concrete, as well as increased the mechanical performance by 17–28%. Also, the hemp fibres with high cellulose content improved the rheology of the concrete due to improve their workability and plasticity.
Poletanovic et al., [75]	0, 0.5%, and 1%	Addition of hemp fibres of 0.5% and 1% led to increase the compressive strength up to 10% and decrease the flexural strength up to 7% and 21%, respectively. Also, reduced the bulk density of mortar up to 5%, while the water absorption ratio of mortar containing 0.5% and 1% hemp fibres increased by 15% and 20%, respectively.
Juradin et al., [76]	0.34%, 0.5%, 0.68% and 1%	Addition of hemp fibres into concrete led to improve the ductility of the samples and not important effected the compressive and tensile strengths. In addition, incorporation a lower percentage of hemp fibres in the concrete achieved better mechanical properties. As well as a higher ductility of concrete could be achieved with samples comprising a lower percentage of hemp fibres.
Wang and Wang [80]	0, 0.18%, 0.36%, 0.54%, 0.60%, 0.72%, 0.84%, 1.06%	Fibre content had a significant role on the compressive and flexural strengths of concrete. Incorporation of hemp fibre in the concrete led to decrease the water absorption and the specific gravity ratios of the concrete. In addition to that, the use of hemp fibres reduced the compressive and flexural strengths of concrete. Wet mix had a better performance than dry mix.
Candamano et al., [81]	0.5%, 1.0% and 1.5%	The addition of hemp fibres treated by $Ca(OH)_2$ had a significant effect on enhance the thermal stability of concrete samples. As well as, the use of hemp fibres resulted to change the workability. While, the compressive strength decreased gradually due to addition of hemp fibres.

concrete without fibres. On the one hand, NF tends to absorb a small amount of water during the fresh concrete stage, and release water when the interior of the sample is relatively dry. The internal curing effect of NF promotes the further reaction of the unhydrated phase and increases the hydration product content. In addition, NF has an effect on the cracking mode of concrete samples under compressive loading, which delays the development of cracks, which is also beneficial to improve the compressive strength of concrete.

4.1.2. Flexural strength

The addition of NF has the greatest effect on the flexural behavior of concrete samples. A numerous studies were conducted with the use of

Table 5
Effect of jute fibre on the concrete properties.

References	Jute fibres	Effect on the concrete properties
Affan and Ali [83]	0% and 0.8%	The use of jute fibres led to increase the voids, thus increased the freeze-thaw cycles number. As well, the water absorption of jute fibres led to increase the proportion of loss in total mass up to 1.86%. The use of jute fibres in the concrete also reduced the pavement concrete thickness.
Hussain and Ali [84]	0% and 5%	The use of jute fibres in concrete led to reduce the compressive strength up to 6% lower than control concrete sample. Nevertheless, the flexural and tensile strengths of concrete were increased by 128% and 13%, respectively, as compared to control concrete. The use of jute fibres also improved the toughness and energy absorption in concrete mixture. Also, addition of the jute fibres led to increase the damping ratio and dynamic elastic modulus of concrete by 100% and 68%, respectively.
Kundu et al., [85]	0% and 1%	The addition of jute fibres into the concrete resulted to increase the mechanical strengths of concrete, especially compressive and flexural strengths up to 30% and 49%, respectively. The use of untreated jute fibre led to delay the reactions essential for cement hydration and produce a weak adhesion between matrix and jute fibre surface.
Razmi and Mirsayar [86]	0, 0.1%, 0.3%, and 0.5%	The use of high content jute fibres in concrete mixtures achieved the better performance for concrete. This was because of the fibre to delay the growth rate of cracks and reduce the cracks extension. The use of jute fibres led to increase the compressive, flexural, and tensile strengths of concrete. However, the use of high content jute fibres in the concrete mixtures did not increase the fracture resistance. Increase the fibre content led to improve the resistance of mixed mode fracture in jute FRC.
Sultana et al., [87]	0, 0.2%, 0.6%, and 1.2%	The use of 0.55 as water/cement ratio, 0.2% vol. and 6 mm length of jute fibres in concrete mixture was the optimum mix design, this mix resulted to the highest compressive and tensile strengths of concrete. Generally, the use of natural jute fibre might be a promising substitute for the traditional costly methods to improve the concrete strength.
Nambiar and Haridharan [88]	0, 1%, and 2%	The use of 1% jute fibre led to increasing the compressive strength while, the use of 2% jute fibres led to a significant decrease in the compressive and tensile strength owing to the lack of bonding between fibres and matrix. However, the use of jute fibres led to reduce the sorptivity coefficient of the concrete due to these fibres reduce the water movement.
Zhang et al., [89]	0, 1%, 2%, and 3%	The use of jute fibres enhanced the flowability of self-compacted concrete. The treatments ways of jute fibres could efficiently enhance the fresh properties, especially the flow and slump values of self-compacted concrete. The use of natural jute fibres could significantly reduce the final cost of the concrete.

Table 6
Effect of kenaf on the concrete properties.

References	Kenaf fibres	Effect on the concrete properties
Mahzabin et al., [96]	0% and 0.45%	The addition of treated kenaf fibre into lightweight foamed concrete had a substantial effect on enhancing the mechanical properties and durability. The use of treated kenaf fibres resulted to increase the toughness loss more than that of untreated kenaf fibres.
Pirmohammad et al., [100]	0, 0.1%, 0.2%, and 0.3%	The addition of goat wool and kenaf fibres enhanced the fracture strength of asphalt concrete. The enhance level was depending on the content and length of the kenaf fibres. The asphalt concrete reinforced by 0.3% kenaf fibres with 8 mm length showed the highest values compared to other mixtures. The addition of kenaf fibres led to further enhance the fracture resistance of asphalt concrete. Thus, the combination of goat wool and kanaf fibres could be used to improve fracture strength.
Elsaid et al., [97]	0, 1.2%, and 2.4%	To achieve acceptance workability, the diameter of kenaf fibre should be less than 9.5 mm with high cement content and coarse aggregate. The use of lower fibre content did not affect the concrete properties. While the addition of higher fibre content led to reduce the compressive strength slightly. However, the kenaf fibres had a positive effect on the improvement of ductile behavior with higher absorption of energy.
Zhou et al., [101]	0, 1%, 1.5%, and 2%	The incorporation of kenaf fibre in the concrete mixtures resulted in to decrease in the spalling and cracks development under flexural and compression, and showed better ductility. Also, the use of kenaf fibre led to the weakness in the interfacial transition zone (ITZ) between cement matrix and kenaf fibres. While the use of kenaf fibre resulted in to decrease in the compressive strength of concrete up to 2.2–46.2% compared to that of normal concrete without fibres.
Guo et al., [102]	0, 0.25%, and 0.5%	The use of 0.25% and 0.5% kenaf fibres in the cement pastes had a significant role in delaying the cement hydration of paste. Thus, the chemical composition and diameter of fibres should be determined when calculating the influence of kenaf fibres on cement hydration. The use of 0.5% kenaf fibres achieved a higher autogenous strain (increase of expansion degree) and higher expansion.
Zadeh and Bobko [103]	0, 1.2%, and 2.4%	The use of treated kenaf fibres in concrete did not significant effect on the porosity-dominated material. The outcomes referred to enhancing the ITZ of aggregate and cement matrix. The incorporation of high-content kenaf fibres led to a weak the ITZ between matrix and fibres related to a high effective water to cement ratio.

NF in FRC. Elayesh [111] reported that a flexural strength of concrete can be considered as a capability of material to bear distortion when exposed to load. Fig. 4 show the effect of NF on the flexural strength of concrete.

From Fig. 4, most of the researchers reported that the flexural strength increased with increase the NF content [106,108]. In general, the internal curing effect of NF increases the compactness of the matrix, which improves the flexural strength of the samples. Meanwhile, the bridging effect of NF cannot be ignored, which can hinder the propagation of cracks in the matrix and increase the fracture energy, as shown in Fig. 5. Gao et al., also found that adding 2% sisal fibre (18 mm, Tensile strength=530–630 MPa) to UHPC increased the flexural strength of the sample by 16.7% [6]. Other study by Wongsa et al., [112] studied the effect of two kinds of NF namely coconut fibre and sisal fibre in different volume fraction on high calcium fly ash-based geopolymer mortars. They observed that the use of NF (coconut and sisal fibres) led

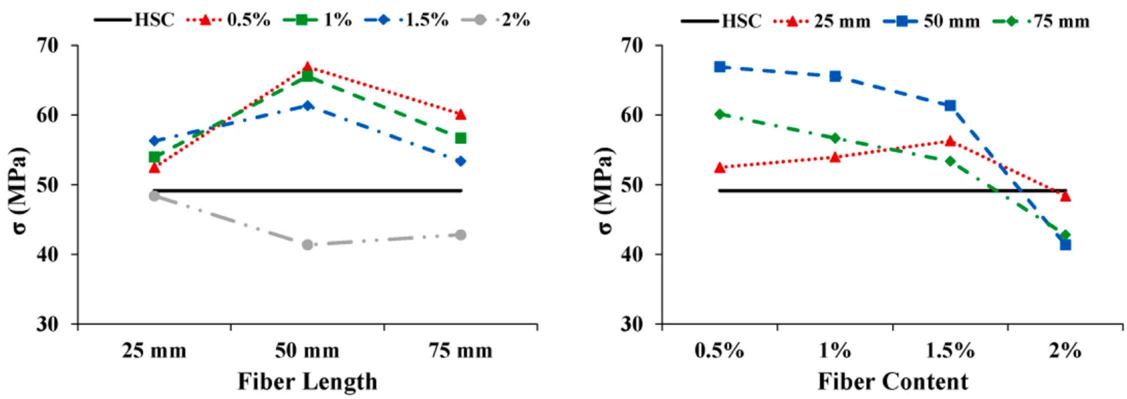

Fig. 3. Compressive strength of concrete with NF, Reproduced under Creative Commons license from [110].

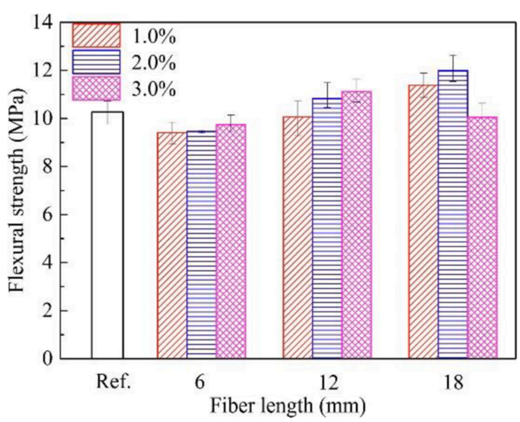

Fig. 4. Flexural strength of concrete with NF at 28 d, reproduced under license number 5491191123234 from [6].

to a considerable improvement in flexural and tensile strengths. However, the compressive strength, ultrasonic pulse velocity, dry density, and workability decreased remarkably. In addition, the results of Zhou et al. also showed that kenaf fibre (Tensile strength=920 MPa and the Young's modulus=GPa) enhanced the flexural strength and toughness of high-strength cement composites better than low-strength cement composites [101]. It can be seen that adding an appropriate amount of NF to the cement-based material can effectively improve the flexural strength of the sample, but this is achieved under the condition that the mixture has good fluidity and uniform fibre distribution.

4.1.3. *Splitting tensile strength*

Similar to flexural strength, NF also significantly enhances splitting tensile strength. The usage of NF in RFC has an important effect in reducing the cracks width while at the same time growing indirect tensile strength. In study by Arivalagan [114], revealed that the usage of fibres was a suitable solution to enhance the tensile strength with increase the curing ages. Numerous researchers studied the concrete properties and examined the effect of NF in different content, types, and lengths as shown in Fig. 6 [110].

From Fig. 6, most of the researchers concluded that the splitting tensile strength increased with increase the fibre content especially with 1% coir fibre (Tensile strength=2450–2750 MPa, Young's modulus=14500–16250 MPa) [108]. While, other researchers observed that the splitting tensile strength of concrete did not effect by addition the NF and this slight effect can be neglectable [106]. Based on the results obtained and compared to the control concrete, the use of 0.5% sisal fibre (Tensile strength=370 ± 7.4 N/mm^2, Modulus of elasticity=3.8 ± 0.07 GPa) and 1.5% polypropylene fibre (Tensile strength=425 ± 8.5 N/mm^2, Modulus of elasticity= 2.52 ± 0.05 GPa) led to increase the tensile strength of FRC by 37.2% and 47.5%, respectively, after 7 and 28 d [115]. The use of NF in concrete led to improve the tensile strength of FRC. Zhao et al. used pineapple leaf fibre (Modulus of elasticity=10.78 GPa) and ramie fibre (Modulus of elasticity=9.99 GPa) to modify cement-based materials, and found that the tensile strength of the samples increased significantly after adding NF, as shown in Fig. 7 [116]. When the content of pineapple leaf fibre was 1.5%, the tensile strength and tensile capacity were higher, and the strain hardening phenomenon was the most obvious.

4.2. *Durability*

The durability of concrete is a significant issue that required further investigation. Therefore, the following sections address the effect of NF on the durability of concrete and find out the advantages and disadvantages beyond the use of these fibres to improve the service performance.

4.2.1. *Water absorption*

Water absorption of any materials has a strictly associated to the concrete durability because of bringing the hurtful materials into the concrete and can be considered a main causes to corrosion

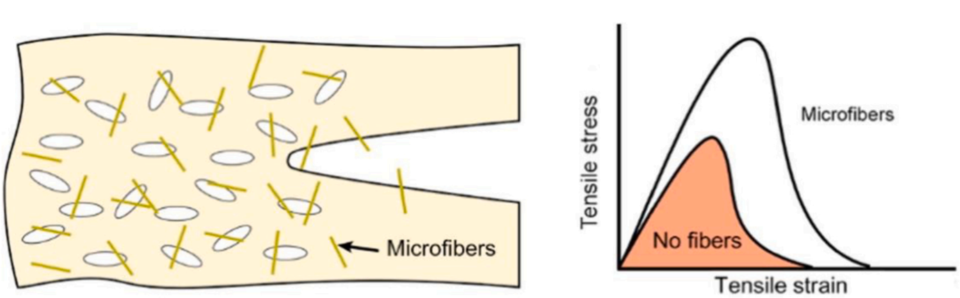

Fig. 5. Strengthening mechanism of NF in cement components, reproduced under license number 5491191227164 from [113].

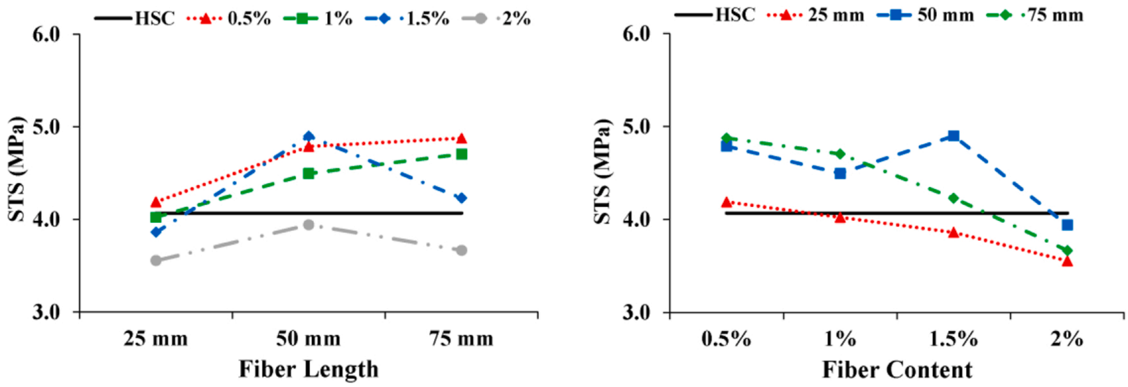

Fig. 6. Splitting tensile strength of concrete with NF, Reproduced under Creative Commons license from [110].

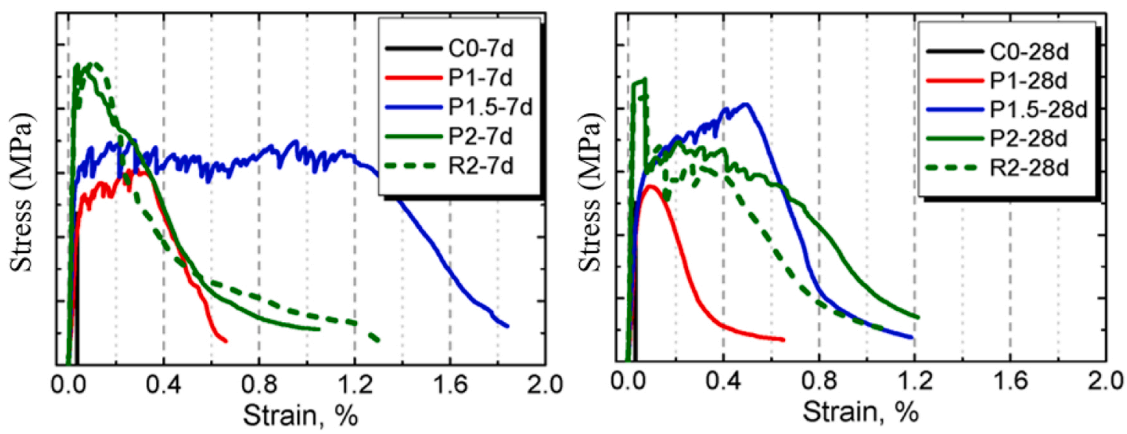

Fig. 7. Tensile stress-strain behavior of sample with pineapple leaf fibre (P) and ramie fibre (R), reproduced under Creative Commons license from [116].

reinforcement bars, cracks, and structural expansion. Therefore, a high durability concrete can be achieved with low water absorption [117, 118]. Kesikidou and Stefanidou [119] used three types of NF as eco-friendly ↱materials namely, kelp, coconut, and jute fibres as additives in 1.5% by mortar volume. ↱All fibres were kept in a water tank for 1 d to avoid further water absorption during ↱the mixing process, and the water absorption of each fibre kind was determined by the variance ↱of weight earlier and afterward soaking into water. ↱They observed that the water absorption of fibre in cement mortars does not display important changes, showing that the fibres adhesion was no capillary voids and strong when shaped around the fibres. However, there are a difference in lime mortars, as mortars with kelp fibre look to have a higher water absorption owing to capillarity compared to jute and coconut fibres mortars. Zhao et al. further investigated the effect of adding pineapple leaf fibre (P) and ramie fibre (R) on the capillary water absorption of cement mortar, as shown in Fig. 8. As the NF content increased, the water absorption of the mortar also increased, mainly because NF provided channels for water penetration [116]. Meanwhile, the water absorption of mortar mixed with ramie fibre was significantly higher than that of mortar mixed with pineapple leaf fibre, which may be related to the internal structure of NF. Abdullah et al. used coconut fibres to modify cement-based materials and found that their water

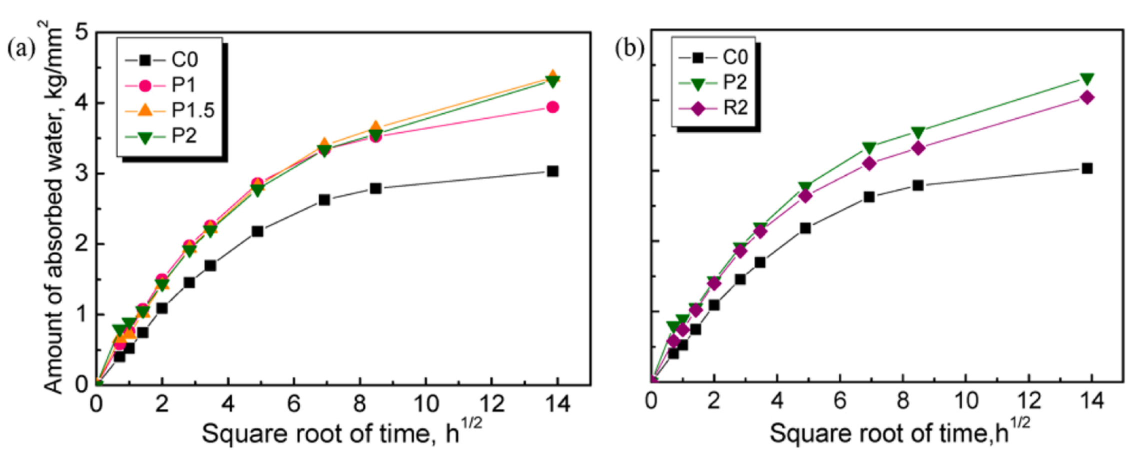

Fig. 8. Water capillary absorption of mortar with different fibre content (a) and fibre type (b), reproduced under Creative Commons license from [116].

absorption increased by 14.52%– 29.03% relative to the plain samples, which was attributed to the high water absorption of NF and increased porosity in the matrix [120].

4.2.2. Chloride penetration

Ramli et al. added coconut fibre to concrete and found that with the increase of NF content, the corrosion resistance of concrete under seawater immersion became weaker, as shown in Table 7 [121]. This result indicated that the drying shrinkage of NF after dehydration and the formation of significant ITZ with the cement matrix was the main reason for the increase in chloride permeability. Ban et al. incorporated bamboo fibres into mortar and found that the samples contained an increased concentration of chloride ions relative to the plain mixture. This study also treated bamboo fibres with glycerol, aluminate ester and silane, and found that aluminate ester-treated bamboo fibre-modified mortars had relatively slightly lower chloride ion concentrations inside the samples [122]. Dávila-Pompermayer et al. used lechugilla NF as an internal curing agent in self-compacting concrete and found that it was beneficial to the improvement of matrix compactness, thereby reducing chloride ion permeability in non-steady state tests [123]. Sarangi et al. tried to use sisal fibre, banana fibre, and human hair fibre to improve the chloride resistance of concrete materials, and found that adding less NF can play a role in reducing the penetration charge due to the effect of discrete and randomly oriented fibres. However, when the three fibres were used in combination, the effect was weakened [124]. In order to improve the chloride ion resistance of NF-reinforced mortar, Gutiérrez et al. used active admixtures to replace part of the cement to improve the compactness of the matrix and ITZ, thereby reducing the chloride ion permeability coefficient of NF-reinforced mortar [125]. Therefore, the use of NF tends to increase the interconnection channels within the concrete, which intensifies the aggressive effect of chloride ions, especially at high dosages. By reducing the content of NF, using hybrid fibres or surface modification to reduce the content of pore channels is the key to improve the chloride resistance of NF-reinforced concrete.

4.2.3. Carbonation resistance

Recently, researchers used NFs to enhance the resistance against carbonations of concrete. Talavera-Pech et al. modified the mortar using sugarcane bagasse fibre and found that the carbonation resistance of the sample was enhanced. This was mainly due to the volume expansion of sugarcane bagasse fibres in an alkaline environment (pH=9–10) and clogging of pore channels (See Fig. 9) [126]. The combined application of cellulose-based flax fibre and wood-based cellulose nanocrystals (CNCs) improved the carbonation resistance of cement composites by Lee et al. [127]. Ramli et al. also found that with the increase of coconut fibre content, the carbonation depth of concrete also increased, which was related to the poor ITZ between the fibre and the matrix [121]. The study by Ban et al. showed that glycerol treatment of bamboo fibres can make the carbonation resistance of NF-modified mortar similar to that of plain mortar compared with aluminate ester and silane treatment groups [122]. Ahmed et al. modified metakaolin-based mortars with date palm and hemp fibres and found that the carbonation resistance of the samples decreased slightly, but not to a large extent [128]. Several recent studies investigated the performance evolution of NF-modified cement components under carbonization curing and found that carbonization curing can effectively enhance the performance of NF-modified cement components and delay the degradation of NF by adjusting the pH of the samples [129–131]. It is worth noting that NF may provide a channel for CO_2 permeation, which provides a potential value for carbonization curing of NF-reinforced concrete.

Table 7
Chloride concentration of coconut fibre reinforced concrete at 180 d (%) [121].

Sample	0–10 mm	10–20 mm	20–30 mm	30–40 mm
Control	0.5	0.08	0	0
0.6CF	0.59	0.12	0	0
1.2CF	0.55	0.08	0	0
1.8CF	0.51	0.08	0	0
2.4CF	0.62	0.2	0.04	0

4.3. Volume stability

The water absorption and toughening effects of NF are crucial for improving the volume stability of cement components. Guo et al. used raw (RKF), alkaline treated (AKF), and alkaline-hydrogen peroxide treated (AHPKF) kenaf fibres to modify the cement paste, and found that adding an appropriate amount of NF could effectively reduce the autogenous shrinkage of the paste, as shown in Fig. 10(a). Meanwhile, Guo et al. also tested the drying shrinkage of kenaf fibre-modified pastes and found that the volume stability of NF-doped pastes was improved. When the content of kenaf fibre was 0.5%, the alkali-treated kenaf fibre could effectively reduce the autogenous shrinkage and drying shrinkage of the paste [102]. In addition, Page et al. found that flax fibres also had the effect of reducing the overall shrinkage of the composite, as shown in Fig. 10(b) [132]. Filho et al. systematically studied the effect of sisal and coconut fibres on the shrinkage deformation of cement mortar and found that adding 0.2vol% sisal fibres significantly reduced free plastic shrinkage. Meanwhile, the addition of sisal and coconut fibres also improved plastic shrinkage, reduced the risk of early cracking, and made the samples self-healing ability [133].

Kouta et al. systematically studied the effect of the content and length of flax fibres on the shrinkage behavior of concrete, and found that NF was effectively reduce total free plastic shrinkage, strain localization of restrained shrinkage and the plastic shrinkage cracking [69]. For drying shrinkage, longer flax fibres provided higher resistance to cracking. Meanwhile, flax fibre also reduced the bleeding content of concrete and improved the early-ages stiffness of the sample, and its internal curing effect also provided a guarantee for the long-term strength improvement. Due to the high water absorption of NF, researchers tried to use it as an internal curing agent and used it to reduce the shrinkage deformation of concrete. Dávila-Pompermayer et al. used lechugilla fibre with a 22-h water absorption ratio of 98% as an internal curing agent to effectively reduce the shrinkage deformation of self-compacting concrete, as shown in Fig. 11 [123]. The results have shown that the use of lechugilla NF reduced the 28-d autogenous shrinkage of cement components by 13.1–54.5%, with better effects at an early-ages.

4.4. Thermal properties

The use of NF modified cement-based material is an effective way to improve its thermal insulation ability. Thermal conductivity is an effective parameter to measure the heat transfer coefficient of thermal insulation materials. He et al. prepared cement board using wood fibre and magnesium oxychloride cement, and studied the effect of processing technology on the thermal insulation performance of cement board, as shown in Fig. 12 [134]. The results have shown that the thermal conductivity of the cement board decreased with increasing wood fibre content, which was related to the density of the sample. Meanwhile, the use of large-sized wood fibres was more effective in reducing the thermal conductivity of cement boards, mainly due to the higher internal porosity of large-sized wood fibres. In addition, increasing the extrusion force also increased the compactness of the NF-reinforced component, thereby increasing its thermal conductivity. Boudjemaa et al. also systematically studied the cement mortar modified with date palm fibres, and found that with the increase of NF content, the thermal conductivity of the samples decreased. Meanwhile, when the date palm fibres absorbed water, the thermal insulation capacity of the samples decreased [135].

Muhammad et al. also studied the effect of different types of NF (jute

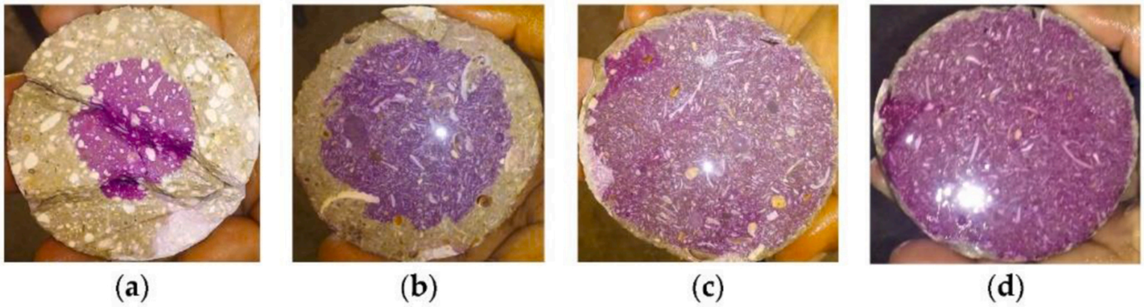

Fig. 9. Carbonation of concrete with cane bagasse fibre, (a) 0%, (b) 0.05%, (c) 1%, and (d) 2%, reproduced under Creative Commons license from [126].

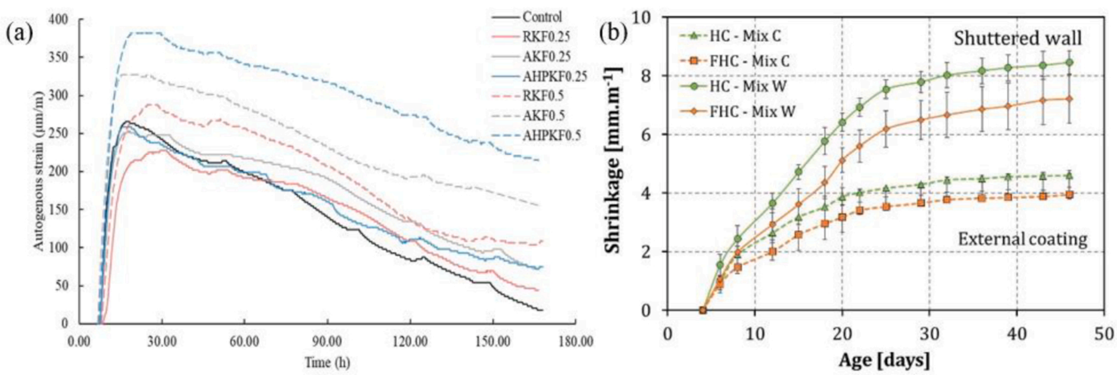

Fig. 10. The autogenous strain (a) and total shrinkage (b) of NF-modified sample. FHC: fibre-reinforced components, and HC: plain sample, reproduced under license number 5491250079511 and 5491241394721 from [102,132].

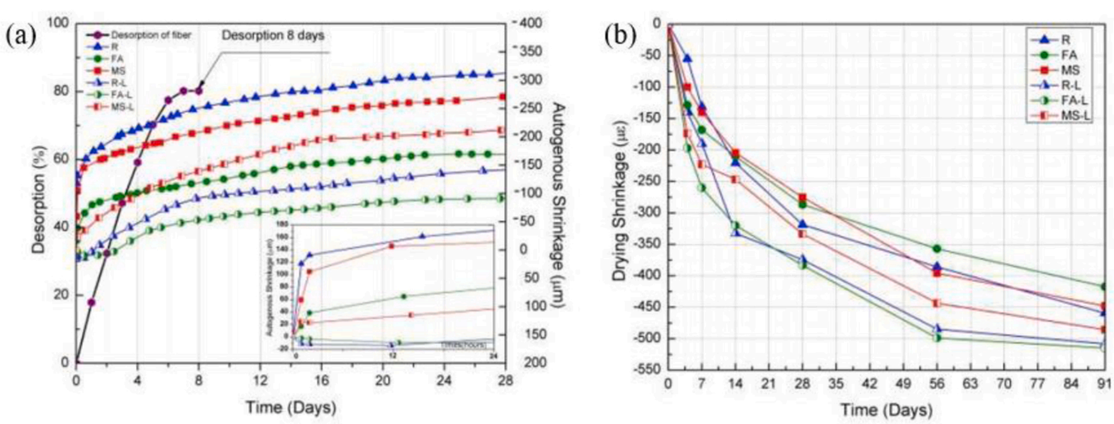

Fig. 11. The autogenous strain (a) and drying shrinkage (b) of NF-modified sample. R, FA and MS: plain sample fibre-reinforced components. R-L, FA-L and MS-L: fibre-reinforced components, reproduced under license number 5491250219366 from [123].

fibres, sugarcane fibres, sisal fibres, and coconut shell fibres) on the thermal conductivity of concrete, as shown in Fig. 13. In general, the thermal conductivity of concrete decreased with increasing NF content, and the coconut fibre-modified samples exhibited the best thermal insulation performance [136]. The study by Trabelsi et al. also showed that the thermal conductivity of concrete decreased as the length of the prickly pear fibres increased [137]. Gencel et al. also obtained similar results using hemp fibre in foamed concrete, and adding hemp fibre was beneficial to reduce the thermal conductivity of foamed concrete [78]. Saghrouni et al. also found that Juncus maritimus fibres had a porous cellular microstructure, which improved the thermal insulation capacity of concrete, and the surface treatment had little effect on the thermal conductivity of the samples [138]. In addition to the pore structure of the fibres, NF may also introduce air bubbles during the mixing process, which also reduces the thermal conductivity of the concrete.

4.5. Microstructure

In recent study, Soroushian et al., [139] investigated the use of different kinds of wood fibres and the effect of fibre to concrete mixture. The scanning electron micrograph (SEM) test has been carried out to show the effect of these fibre types on the microstructures of FRC. They observed that the matrix nearby fibre was seen to be slightly porous, proposing a weak fibre-matrix connecting. As reported that by different studies, an assortment of plant fibres had been applied in FRC production [140], as illustrated in Fig. 14. The strength and durability of concrete mostly rely on the fundamental properties of fibres and the connection strength between concrete matrix and fibres [141]. Other

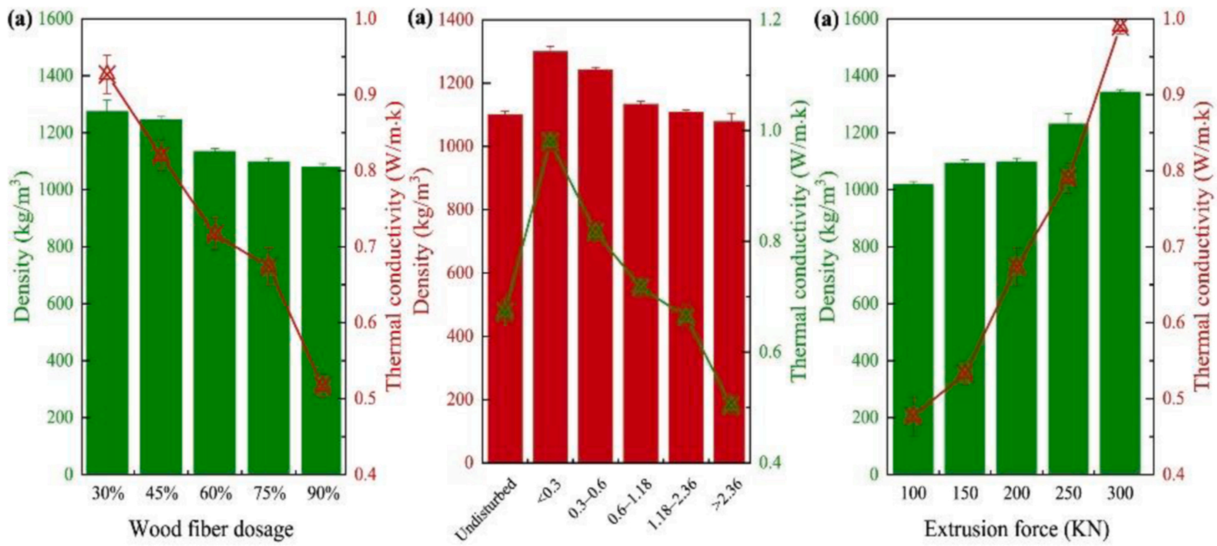

Fig. 12. Thermal properties of magnesium oxychloride cement board, reproduced under license number 5491250412272 from [134].

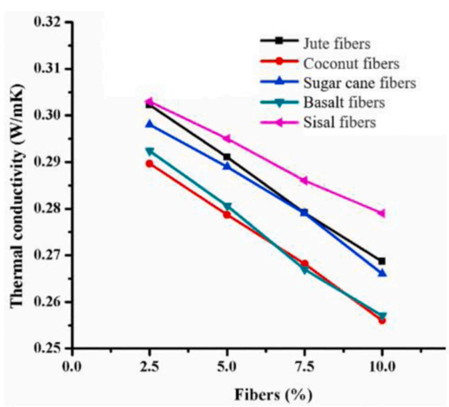

Fig. 13. Effects of NFs on thermal conductivity of lightweight concrete, reproduced under license number 5491250562606 from [136].

study by Wongsa et al., [112] investigated the influence of two kinds of NF namely coconut fibre, and sisal fibre with glass fibre in different volume fraction on high calcium fly ash-based geopolymer mortars. They adopted SEM test to examine and analyzed the morphology and microstructure of fibre-reinforced geopolymer mortars. They detected that the geopolymerization matrix produces was homogenous and dense with simply detected with fly ash particles as presented in Fig. 14. But, the SEM images of the fibre reinforced-geopolymer mortar showed the coarser surface and more unequal stripes of coconut fibre and sisal fibre whereas glass fibre has a more uniform and smoother surface [112].

Wei et al. tested the XRD patterns of pristine sisal fibres and embedded cement and metakaolin samples after 5, 15, and 30 dry-wet cycles (See Fig. 15) [142]. The ettringite peaks were present in all fibres in the cement paste, whereas the $Ca(OH)_2$ peaks were present only in fibres immersed in a neat cement matrix. The peaks of C-S-H and calcium carbonate in the fibres became stronger as the number of dry-wet cycles increased, indicating that NF was degraded and the cement phase remained in the fibres. The contents of C-S-H and C-A-S-H in the fibres also increased with the increase of the metakaolin content, which also indicated that the addition of metakaolin improved the interfacial bonding properties. With the increase of the number of dry-wet cycles, both the fibre crystallinity index and the crystallinity percentage increased, and the addition of metakaolin could effectively reduce the fibre crystallinity index in the cement matrix.

The thermal analysis results of NF in the cement matrix were shown in Fig. 16, and its mass decrease was sequentially caused by the evaporation of moisture inside the fibre (50–110 ℃), the decomposition of part of hemicellulose and lignin (270–350 ℃), the cellulose and the rest of the lignin caused by the decomposition of elements (high temperature areas) [142]. The early weight loss of fibres in the cement composition was lower than raw fibres because NF lost water in the cement composition and exerted an internal curing effect, and the degradation and damage of the cell wall also led to the reduction of its water retention rate. Meanwhile, the use of metakaolin effectively reduced the alkalinity of the mixture, which reduced the corrosion degree of NF.

5. Enhancement technology for NF-reinforced cement components

5.1. Optimized cementitious components

Improving the properties of NF-reinforced concrete by optimizing the cementitious components is a relatively simple route. On the one hand, the use of admixtures improves the compactness of the cement matrix and enhances the interface properties between the matrix and the fibres. Meanwhile, the use of admixtures reduces the soluble alkali content of the cement mixture and consumes silicates, which reduces the alkalinity of the mixture. The lignin and hemicellulose of NFs are essential for their stability. The decomposition of the amorphous material in an alkaline environment breaks the discrete CNCs and causes the degradation of NF, as shown in Fig. 17. As the degradation process progresses, hydration products such as C-S-H and soluble silicates gradually penetrate into the cell wall, which in turn leads to mineralization and embrittlement of NFs. Cell wall mineralization also results in fibre embrittlement, reduces strength and strain capacity. Wei et al. used metakaolin to replace 30% of OPC to effectively reduced the alkalinity of the mixture and improved the durability of sisal fibres under the action of drying and wetting cycles [142]. Filho et al. effectively improved the degradation resistance of sisal fibre by replacing part of the cement with slag [129]. Mohr et al. more systematically studied the aging resistance of kraft pulp fibre in cement matrix by multi-admixture system, and found that multi-admixture system could effectively reduce the damage failure rate of NF under the action of dry and wet cycles [143]. This study showed the use of metakaolin, slag, and silica fume to replace part of the cement, which reduced the precipitation of calcium hydroxide and ettringite, and increased the content of supplementary C-S-H. Filho et al. also effectively improved the durability of sisal fibre by modifying

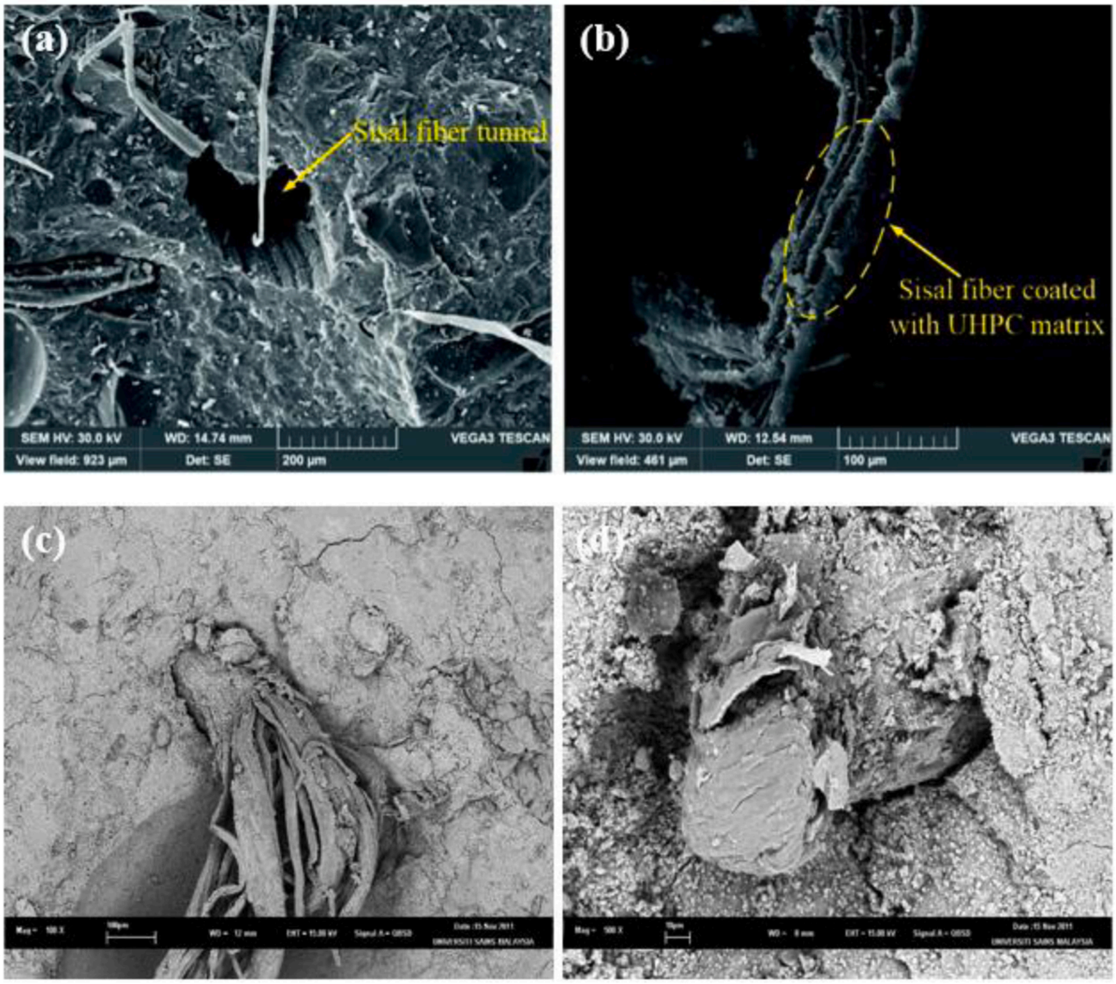

Fig. 14. SEM images of concrete with different NFs, (a and b) sisal fibre, and (c and d) coconut fibre, reproduced under license number 5491260600798 and 5491260726211 from [6, 121].

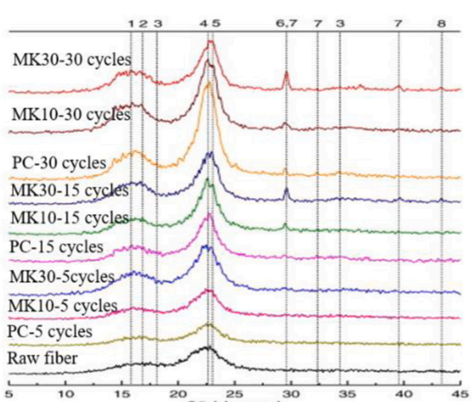

Fig. 15. XRD pattern of sisal fibres in cement (PC), 90%PC+ 10%metakaolin (MK, MK10), and 70%PC+ 30%metakaolin (MK30) after dry-wet cycle, reproduced under license number 5491261005988 from [142].

the cement matrix with calcined clays [144]. Modification with admixtures was more significant than expected, with the study by John et al. showing that in low alkaline slag cement, coir fibres remained relatively intact after 12 years [145].

5.2. Pretreatment for NFs

Since NF easily absorbs water and loses water under different humidity environments, it has poor volume stability and is easily decomposed. There are many methods for NF pretreatment, which are mainly divided into physical methods, chemical methods and combined methods. There is no doubt that the physical modification is relatively easy, and the chemical composition of NF does not change during the process, while the surface morphology and physical state are changed. During the heat treatment, the water is gradually lost, the lignin is rearranged, and the hemicellulose is degraded, which reduces the possibility of pores and internal stress inside the cement-based material [146]. The steam blasting treatment by Claramunt et al. caused the expansion and rupture of NF under high pressure and increased the roughness of the NF surface, which improved the bond between the NF and the cement matrix [147]. Some researchers have also used hornification treatment to subject NF to dry-wet cycles and cause it to produce irreversible shrinkage and internal hydrogen bonds [148]. Some scholars also use plasma method for surface treatment of NF. Therefore, physical methods are considered to reduce the water absorption of NF and improve its bonding performance with the cement matrix by changing the size, morphology, and texture of the NFs.

Compared with physical treatment, chemical treatment generally enhances the number of active groups on the fibre surface by changing the chemical composition and structural characteristics of NF. Alkaline treatment is the most common method, which changes the ordered

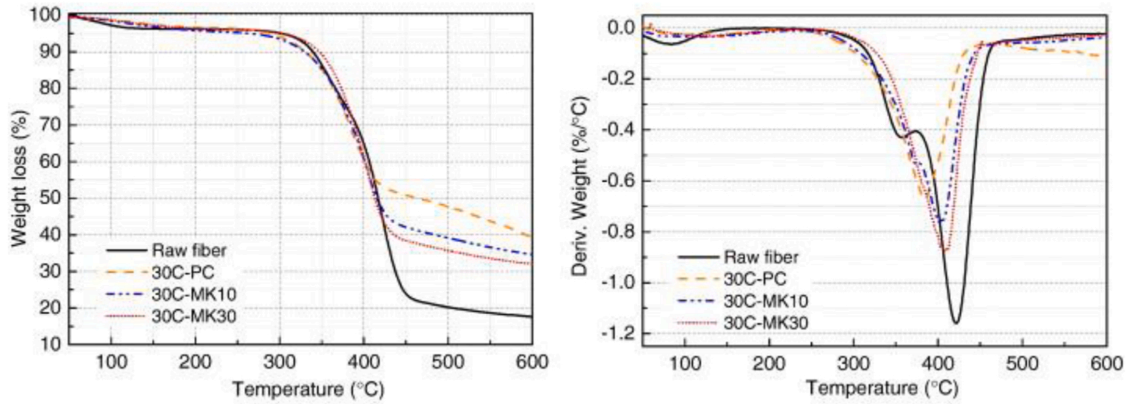

Fig. 16. Thermal analysis of sisal fibres in cement (PC), 90%PC+ 10%metakaolin (MK, MK10), and 70%PC+ 30%metakaolin (MK30) after 30 dry-wet cycle, reproduced under license number 5491261005988 from [142].

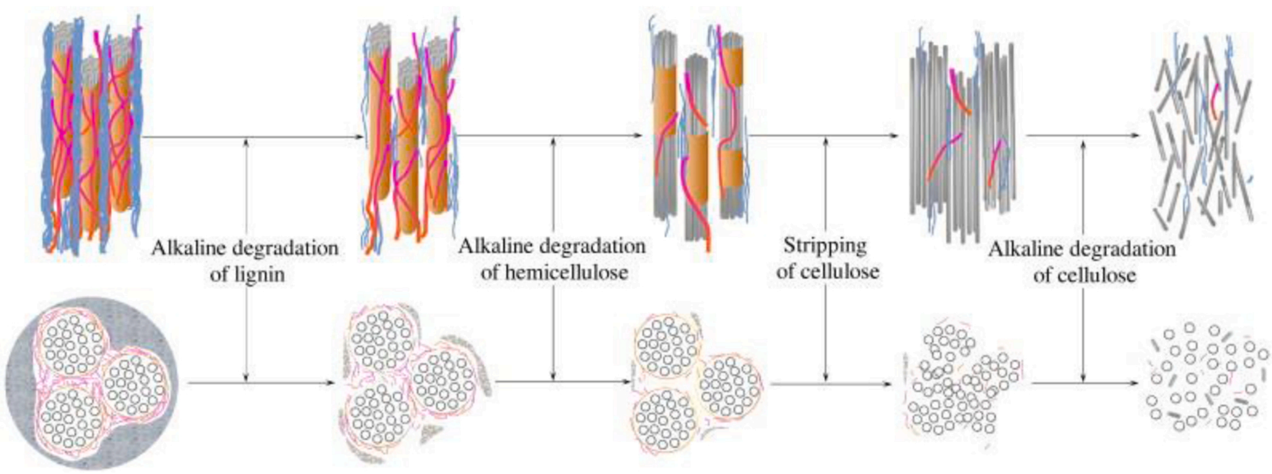

Fig. 17. Degradation of NFs in an alkaline environment, reproduced under license number 5491261005988 from [142].

orientation of the highly deposited crystalline cellulose in lignocellulosic NFs, reduces the amorphous content, and increases the crystallinity of NFs. Meanwhile, the alkali treatment also depolymerizes the cellulose to form short chains and increases the surface roughness of the NF, which also increases the tensile strength of the NFs, as shown in Fig. 18 [149]. As shown in Fig. 19(b), pectin, hemicellulose, fat and wax were also removed in the alkali-treated hemp fibre [74]. There are also studies soaking NF in acetic acid and acetic anhydride and using sulfuric acid as a catalyst to speed up the reaction rate. The reaction of CH_3CO- with -OH of fibre decreased the hydrophilicity of NF and increased the surface roughness, as shown in Fig. 19 [150]. Narendar et al. also reduced its hydrophilicity by treating with acrylic acid to make the carboxyl group form an ester bond with the cellulose hydroxyl group [151]. In addition to reducing the hydrophilicity and roughness of NFs, researchers have also used surface modification or surface sealing strategies. In polymer graft co-polymerization, synthetic polymers are graft-copolymerized on NF [152]. In addition, the use of silane coupling agent is also a good method, which can fill the internal pores of NF and play a role in sealing and waterproofing. Of course, it also interacts with the matrix at one end and with the hydrophilic fibres at the other end [153]. Of course, some researchers have also tried to combine various strategies to strengthen the performance of NF in cement-based materials, and achieved good results [154].

5.3. *Strengthen the interfacial properties between NFs and cement components*

The interfacial properties between cement matrix and NFs are the key to the performance of NF-reinforced components. The interfacial properties are determined by chemical bonding, mechanical interlocking at the surface of the roughened NF and surface energies of the cement components. The relative humidity inside the specimen has a significant effect on the pull-out behavior and tensile response of NFs in the cement components. Ferreira et al. found a tendency for the tensile strength of NFs to increase at low relative humidity due to the formation of new hydrogen bonds, while at high relative humidity there was a decrease of tensile strength by the breaking of hydrogen bonds [1]. Gao et al. studied the interfacial bonding properties of sisal fiber and UHPC under steam curing (90 ℃) and standard curing (20 ℃, RH≥95.0%) conditions [56]. The research results showed that the bonding between sisal fiber and matrix under standard curing conditions was lower than that under steam curing conditions, which was caused by the thermal shrinkage of sisal fibers at high temperature. Meanwhile, the steam curing conditions significantly increased the crystallinity of sisal fibers, which was also detrimental to their interfacial properties. Similarly, Soroushian et al. also found that carbonation curing was improve the interfacial properties between NF and cement [158]. Therefore, it is very important to adopt the curing conditions used. In addition to proper curing conditions, surface modification is also one of the most commonly used methods to enhance the interfacial properties of NFs and cement components. Ferreira et al. used carboxylated styrene

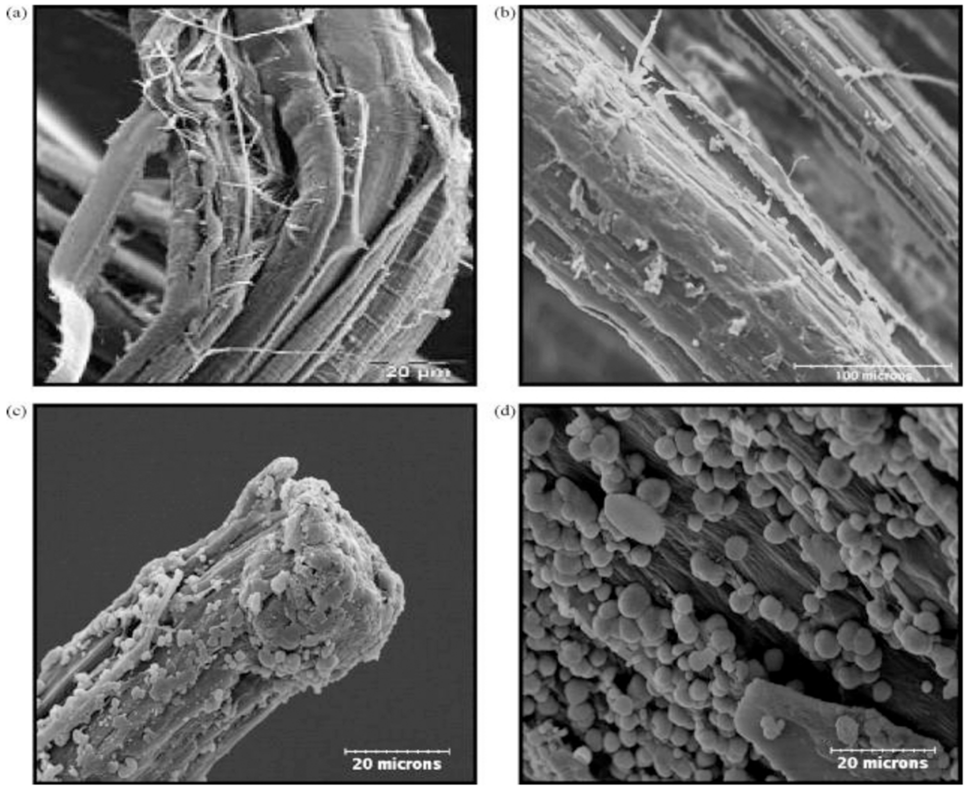

Fig. 18. SEM micrographs of cortical fibres before (a and b) and after immersion in a lime-saturated solution (c and d), reproduced under license number 5491270322898 from [149].

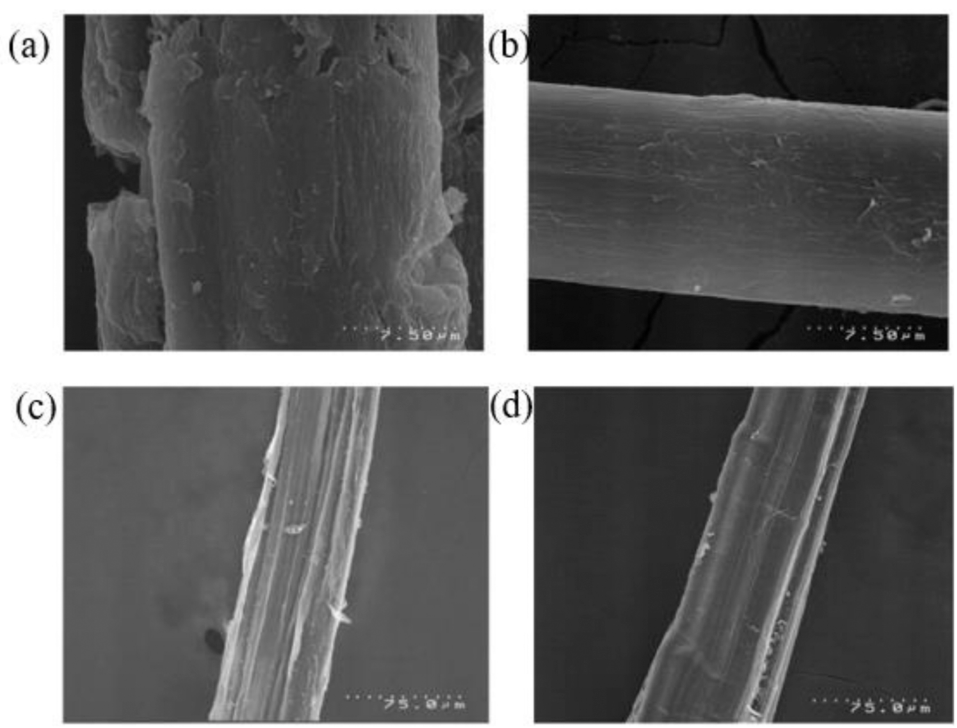

Fig. 19. SEM images of (a) untreated and (b) alkali treated hemp fibres, (c) acetic anhydride and (d) maleic anhydride treated hemp fibres, reproduced under license number 5491270489415 from [74].

butadiene rubber to modify NFs and found that both tensile strength and adhesion were improved, as shown in Fig. 20 [2]. Since the polymer promoted good chemical and physical bonding of NF to the cement matrix, the high frictional bond strength enabled it to exhibit slip hardening behavior. This was mainly due to the increased chemical bond between the treated NFs and the cement matrix, which increased

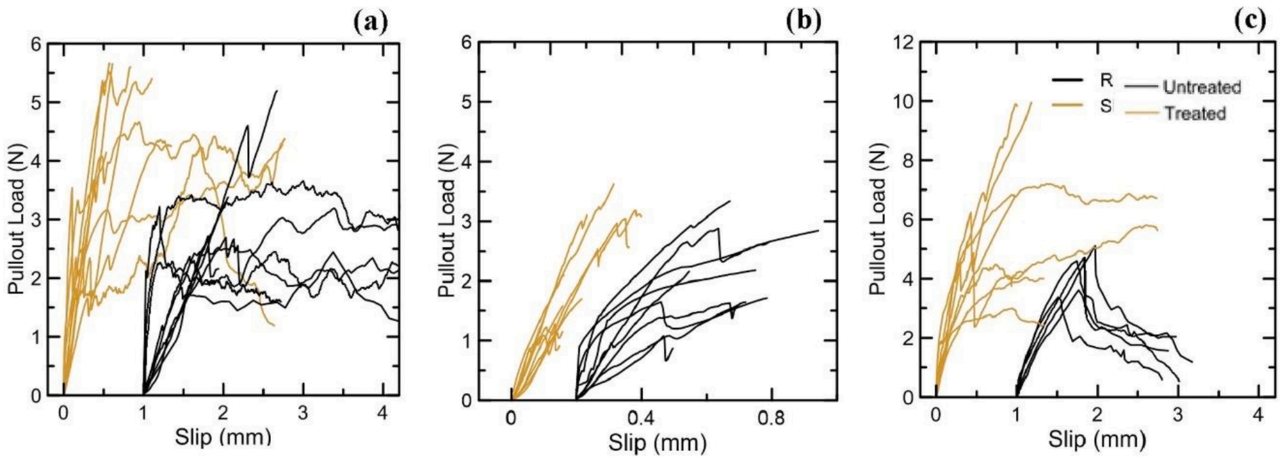

Fig. 20. Force-slip curves from pullout test of treated and untreated NFs, (a) Curauá, (b) Jute, and (c) Sisal. reproduced under license number 5491271404561 from [2].

the maximum load during fiber extraction. Tran et al. used amorphous silica products to treat carbon fabrics and improved the bonding performance with cement matrix, mainly because a thin layer of C-S-H gel was produced on the surface of the treated fibers to have good adhesion [5].

5.4. NF-based fabric

To improve the dispersion of the fibres and enhance their overall synergy, the researchers have developed 2/3-D fabrics. Artificial fibre fabrics have been widely studied in cement-based materials, and compared with synthetic fibres, natural fabrics need to be prepared into fabrics to enhance the performance of cement-based materials. NF can be woven into fabrics of different morphologies, orientations and densities, and typical 2D and 3D NF fabrics are shown in Fig. 21. Mohr et al. produced aligned fibre sheets from pulp fibres and found that the fabrics were significantly tougher than equal volume fibres [155]. Hakamy et al. also used a double hemp fabric, which improve the fracture toughness from 0.356 to 0.656 MPa$^{1/2}$, and the flexural strength of the cement paste from 5.18 to 6.87 MPa. Most of the current research is on artificial fibre fabrics, but few studies apply NF-based fibre fabrics in cement-based materials, and the influence of fibre type, arrangement, direction, and weaving process on cement-based materials needs to be further studied.

5.5. Optimize curing strategy

In order to reduce the alkalinity in the cement mixture, the researchers tried to improve the durability of NF in cement concrete using a carbon curing strategy. Almeida et al. used brief accelerated carbonization to enhance the aging resistance of NF in cement components and also improve the compactness of the cement matrix. Meanwhile, the fibres (pulled out from the matrix) in the accelerated carbonization group had hydration products adhered to the surface and the number was smaller than that in the non-carbonized group, which indicated that the bonding between the NF and the matrix in the carbonized group was tighter (See Fig. 22) [131]. The work of Tonoli et al. also showed that carbonization curing improved the aging resistance of NF in cement-based materials, and the toughness of carbonized samples increased by about 80% [130]. In general, carbonization curing also increased the compactness of the matrix and decreased the porosity, while strengthening the ITZ between the matrix and NF, which significantly improved the flexural strength of the cellulose fibres reinforced samples [158]. Undoubtedly, in low carbon context, the use of multiple carbonization pathways (e.g. atmospheric carbonization, pressure carbonization and wet carbonization) to further improve the aging resistance of NF in cement concrete has become an important topic.

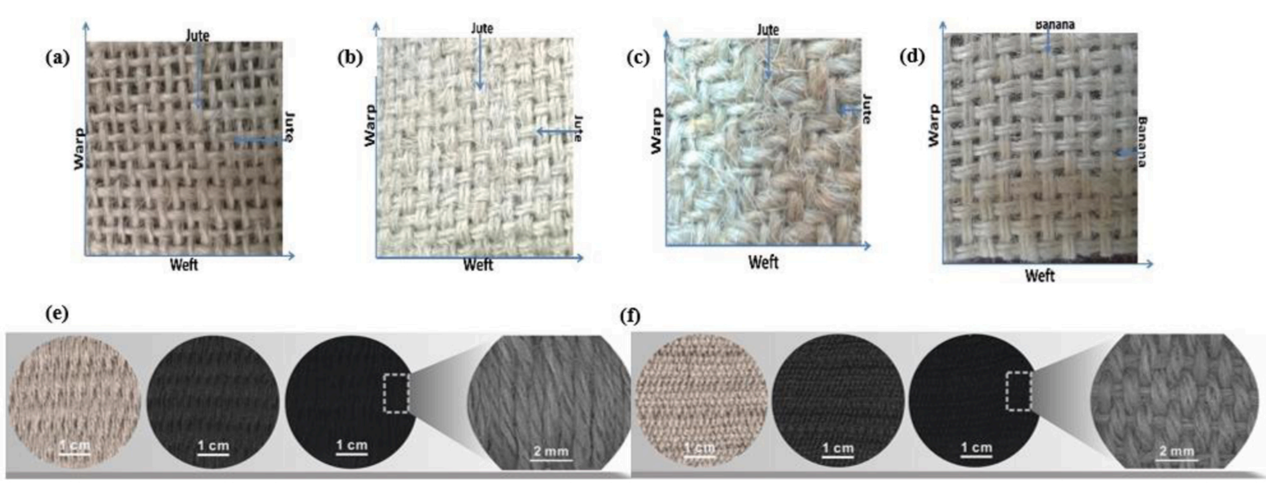

Fig. 21. The NF-based fabrics. (a) 2D Jute-plain, (b) 2D jute-basket, (c) 2D jute-herringbone, (d) 2D banana-basket, and (e, f) 3D hierarchical tree-shaped biomimetic flax fabric, reproduced under license number 5491281369530 and 5491281451556 from [156,157].

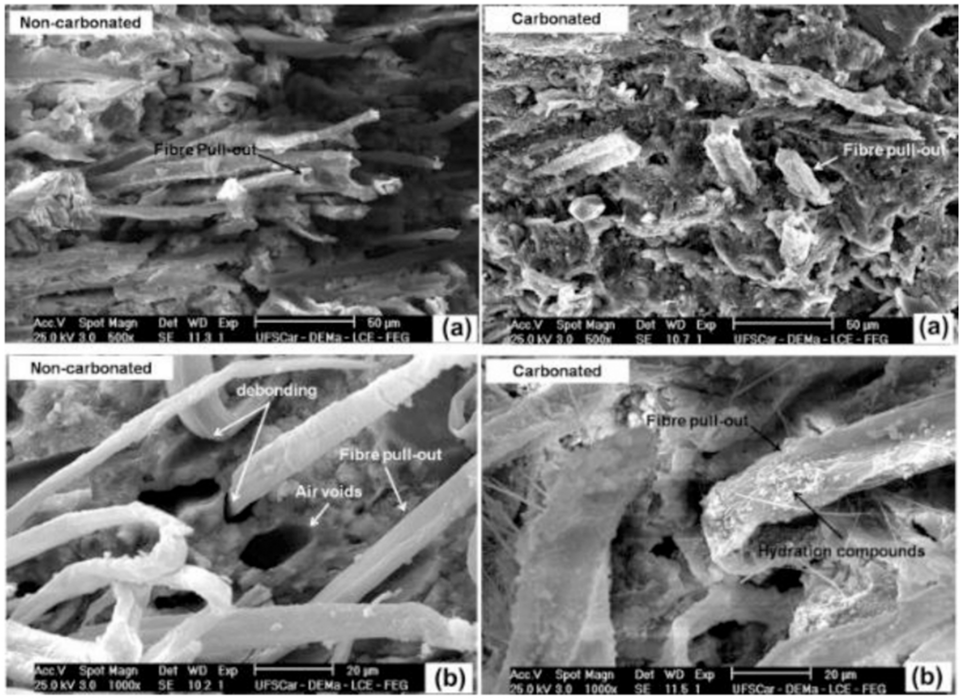

Fig. 22. SEM of eucalyptus pulp fibre-reinforced cement composites, reproduced under license number 5491290060702 from [131].

5.6. Nanocellulose

Another high-value utilization of NF is to convert it into CNC or cellulose nanofibre (CNF). Numerous studies have shown that it is feasible to extract CNC and CNF from wood and plant fibres, and their physical and chemical properties are different. In general, CNCs are only a few hundred nanometers, while CNFs are a few micrometers. CNC has a filling effect in cement-based materials and provides nucleation sites for hydration reaction, and the addition of CNF to cement-based materials also has a toughening effect. The study by Jiao et al. showed that the active hydroxyl and carboxyl groups in CNF formed hydrogen bonds or bridging compounds with hydration products, which effectively improved the microstructure of the samples, thereby enhancing the strength of the cement components, as shown in Fig. 23 [159]. Compared with mechanical fibrillation to obtain CNF, the acid hydrolysis preparation process of CNC is more complicated. However, the improvement effect of CNC for cement components cannot be ignored. The study by Dousti et al. showed that CNC reduced the porosity of cement samples by 33% and increased the 24-h strength of the samples by 60% [160]. Cao et al. further explained the issue and stated that the increased hydration of the CNC-doped cement samples was caused by steric stabilization and short circuit diffusion, which increased the flexural strength of the samples by 30% [161]. A previous study showed that the flexural strength and flexural modulus of sisal nanofibre-reinforced mortar were increased by 36% and 71%, respectively, compared with sisal microfibre-reinforced mortar [162]. Compared with traditional NF, CNC and CNF have better strength gain but their cost is higher and the preparation is more complicated. Therefore, developing the preparation process of novel CNFs and CNCs and further studying their influence mechanism on cement-based materials becomes the goal of the next stage.

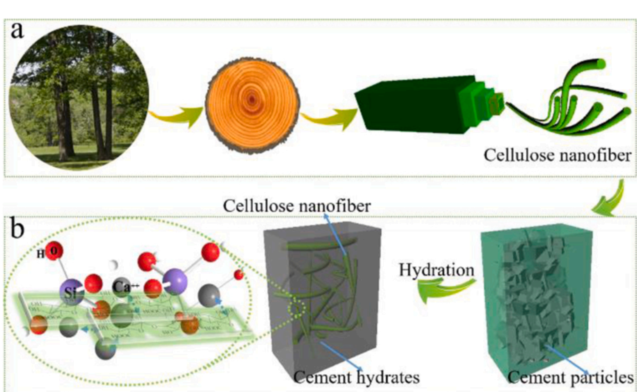

Fig. 23. CNF in the cement component, Reproduced under Creative Commons license from [159].

6. Application of NF-reinforced composite materials

Availability and low cost of NF made it acceptance as a building material in construction industry [163]. Therefore, a numerous studies were conducted to assess the use of different NF like vegetable fibres [163] and caranan fibre (mauritiella armata) [164], and studied the use of natural curaua fibre treated by NaOH at different proportions (0%, 1%, 2%, and 3%) as a reinforcement mortar used for plastering works. They observed that the mechanical properties of cement mortar improved remarkably but the workability was negatively affected due to the addition of 3% fibre content. In addition to that, the durability of mortar improved significantly due to addition a 2% fibres but the use of 2%– 3% fibre led to considerably decrease the workability [163]. The use of NF as reinforcement materials in concrete structures has typically related to the manufacture and repair of beams [165,166], which refers to the significance of the production of high-performance and eco-friendly concrete structures (See Fig. 24). Thomas and Stalin [166] used of sisal fibres to enhance the concrete beams, the use of sisal fibre as reinforced cementitious composites in concrete beam was the most studied among other section.

The UHPC doped with NF is widely used on structural members such as houses and bridges, as shown in Fig. 25. The fibre choosing for development an UHPC is an important to determine ductility, stiffness, and strength. The incorporation of NF has a positive effect on the improvement the overall performance of UHPC. It assists to prevent crack propagation, strain hardening behavior, and multiple cracking.

Fig. 24. Application case of NF in reinforced concrete beams, reproduced under license number 5491290642595 from [167].

Fig. 25. Structural applications incorporating natural sisal and jute fibre high-strength components, reproduced under license number 5491300556102 from [171].

The fibre functionality depends on diameter, length, and tensile strength [168]. The bridging stress affected owing to fibre pull out and fibre siding. Generally, the performance of UHPC incorporating NF can be reinforce of stress against cracks [169,170]. High performance concrete can be obtained by the existence of fibres in concrete.

7. Environmental influence on NF

It is well known that the main advantage of NF depends one decreasing the environmental burdens as compare with other industrial fibre materials used for the same purpose. Numerous studies investigated the effects of NF on the concrete mixtures and environmental impacts such as wood wool, wood fibre, sugarcane or coconut or oil palm, straw, chipped quila bamboo, sheep wool, rice straw, natural tannin-based foams, moss/straw composites, mycelium composite, cork, flax or hemp or jute or kenaf [172–174]. Minimization of the environmental issues is mainly depending on the decreasing the energy requirements, minimizing the cost of the final products, and reducing the CO_2 emission and other toxic gases due to burning expanded vermiculite, mineral fibres, glass fibre, mineral wool, etc.

Availability, the NF in abundant quantity made it a renewable material and not depletion, thus can be considered a sustainable material and can result in a reduction ↱of economic and environmental burdens [175]. Numerous types of NF are available in large quantities that can be used to ↱enhance the concrete in various fields. In terms of cost, usually the cost of materials is a main factor to use the NF or not in concrete manufacturing. Numerous studies reported that the insulation from coconut wood, cork, and pith fibre ↱has a higher cost than that of conventional building insulation. The assessment requirements to reduce the cost might be by ↱adopting locally abundant NF as ↱an elementary source in a certain country; as well as the manufacturing processes by natural ventilation or sunlight, which do not require further energy and cost.↱ For instance, to produce the NF, it should be considered the collection and processing costs that could by costly if compared with other planting area [176]. The jute fibres that are extracted from the plants that are widely in India and Bangladesh ↱consequently the transportation process to use it to other countries might be ↱caused to further negative environmental effects [177]. Economically, the NF must be used and applied when they are abundant in a certain area, therefore it is better to use the jute fibres in India and Bangladesh↱ and reed fibres in ↱European countries↱ [178]. In terms of climate change or global warming issue, the concrete made of the bamboo fibres and sugar cane bagasse fibres has a positive effect on the environmental aspect in study by Riofrio et al., [179]. They concluded that the production methods of NF have better environmental effect than synthetic fibres.

8. Conclusions and recommendations

Due to the demand for sustainability in raw materials usage, natural fibre (NF)-reinforced cement concrete materials are constantly developing. Although the properties of NF-reinforced cement components have been extensively studied, the development of novel NFs suitable for cement concrete materials and their performance enhancement requires further research. From discussions above, the following conclusions can be drawn.

(1) NF is degradable and is a sustainable replacement for synthetic fibres. The high-value utilization of NF is beneficial to fill the vacancy of raw materials and reduce the use of synthetic fibres, thereby improving the environmental benefits of cement concrete materials.
(2) NF has good toughness, and adding an appropriate amount of NF has a positive contribution to the flexural and tensile strength of cement concrete materials. For compressive strength, the content of NF should not be too high.
(3) Pretreatment of NF is the key to improve its performance and aging resistance in cement components, and it is an effective method to modify the surface of NF to bond with the cement matrix.
(4) NF has a positive effect on reducing the bulk density of cement components and improving its sound absorption and thermal insulation properties, but it is often not conducive to the development of pore structure and increases the permeability of samples.
(5) Reducing the degradation of NF in cement concrete materials is the key to maintaining their properties, and optimizing the cementitious components and curing regime is an effective measure. Meanwhile, the effects of various admixtures and different carbonation regimes on the degradation behavior of NF need to be further investigated.

Based on the above review, the following points need to be further investigated and discussed.

(1) It is difficult to achieve the performance requirements of concrete production with a single NF, so it is also a good choice to use multiple NF reinforcement or with synthetic fibres. However, the effect of NF-based hybrid fibres on the properties of cement components needs to be further investigated.
(2) In general, pretreatment is a method to improve the performance of NF in cement concrete materials by reducing the water absorption of NF and improving its surface roughness, but its performance with the cement matrix needs to be further characterized by testing methods such as single-fibre pull-out.
(3) The durability information of NF-reinforced cement components exposed to natural environment is missing, which is beneficial to understand the performance evolution of NF in real service environment.
(4) The use of NF as a raw material for concrete production is economical and eco-friendly, but it is necessary to monitor the long-term performance of NF-reinforced cement components for life cycle assessment to judge their long-term economic and environmental benefits.
(5) The use of NF in advanced cement concrete materials will be a major topic in the future. For example, NF is used as an internal curing material in UHPC to reduce the shrinkage behavior of cement components with low water-to-binder ratio. Use NF to replace part of synthetic fibres to produce ECC to reduce its cost.
(6) Both physical and chemical means can effectively improve the durability of NF in cement components, and the possible synergistic effect of combined physical and chemical means needs to be further investigated. Meanwhile, there is a need to develop a modification process that is more economical, eco-friendly and suitable for industrial production.
(7) Combining advanced technology and means is one of the effective ways for high-value utilization of NF. Weaving NF into 2D/3D fabric and using it to enhance the cement component can improve fibre dispersion and increase its toughness, but the related NF types and weaving parameters need further research. Extracting cellulose nanocrystal or cellulose nanofibre from NF and adding it to cement components can also improve its performance, but further increase of the extraction ratio and more in-depth research are needed.

CRediT authorship contribution statement

Hussein M. Hamada: Conceptualization, Funding acquisition, Writing – review & editing. **Jinyan Shi:** Formal analysis, Writing – original draft. **Mohammed S. Al Jawahery:** Formal analysis, Investigation. **Ali Majdi:** Methodology, Writing – review & editing. **Salim T. Yousif:** Validation, Visualization. **Gökhan Kaplan:** Investigation, Writing – original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

None.

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