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Review

Natural Kenaf Fiber and LC^3 Binder for Sustainable Fiber-Reinforced Cementitious Composite: A Review

Mohammad Hajmohammadian Baghban [1,*] and Reza Mahjoub [2,*]

[1] Department of Manufacturing and Civil Engineering, Norwegian University of Science and Technology (NTNU), 2815 Gjøvik, Norway

[2] Civil Engineering Department, Faculty of Engineering, Khorramabad Branch, Islamic Azad University, Khorramabad 6815139417, Iran

* Correspondence: mohammad.baghban@ntnu.no (M.H.B.); mahjoub@khoiau.ac.ir or r_mahjoob@yahoo.com (R.M.); Tel.: +47-48-351-726 (M.H.B.); +98-91-2372-4133 (R.M.)

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Abstract: Low impact on the environment and low cost are the key drivers for today's technology uptake. There are many concerns for cement production in terms of negative environmental impact due to greenhouse gas (GHG) emission, deficiency of raw materials, as well as high energy consumption. Replacement of the cement by appropriate additives known as supplementary cementitious materials (SCMs) could result in reduction in GHG emission. Limestone-calcined clay cement (LC^3) is a promising binder in the concrete sector for its improvements to environmental impact, durability, and mechanical properties. On the other hand, the advantages of fiber-reinforced concrete such as improved ductility, versatility, and durability have resulted in increasing demand for this type of concrete and introduction of new standards for considering the mechanical properties of fibers in structural design. Thus, using natural fibers instead of synthetic fibers can be another step toward the sustainability of the concrete industry, which is facing increasing demand for cement-based materials. This review studies the potential of natural Kenaf fiber-reinforced concrete containing LC^3 binder as a step toward green cementitious composite. While studies show that energy consumption and GHG emission can be reduced and there is a significant potential to enhance mechanical and durability properties of concrete using this composition, adjustment of the mix design, assessing the long-term performance and standardization, are the next steps for the use of the material in practice.

Keywords: supplementary cementitious materials; natural fiber; LC^3; kenaf fiber; mechanical properties; durability; calcined clay; limestone

1. Introduction

Introducing environmentally friendly materials is one of the most fascinating research fields in engineering. In civil engineering and related disciplines, concrete is a high-demand material for the building and construction sector. Nearly one ton of CO_2 is released in the production of every ton of ordinary Portland cement (OPC) [1–3]. In addition, SO_2 and NO_x which have a role in greenhouse effects and acidic rains are also released during OPC manufacturing [4]. Therefore, different countries and communities should have plans to reduce air pollution. For example, the European Commission has a plan to reduce CO_2 emissions under the EU's emissions trading system, to speed the transition to a low-carbon economy in four phases by 2031. Scientists are continuously trying to improve concrete mixes not only to enhance different properties but also to reduce the material impact on the environment. Fiber-reinforced concrete and supplementary cementitious materials (SCMs) have also emerged in alignment with such goals. While fiber-reinforced concrete is becoming more commonly used and fibers are becoming an alternative to steel reinforcing bars, using natural fibers would be interesting from a sustainability point of view [5]. On the other hand, the cementitious binder needs to be compatible and in alignment with sustainability goals, which has sparked the interest in using natural fibers. There is still an important issue regarding the use of natural fibers in the cementitious binder as natural fiber-reinforced concrete (NFRC). The main drawback of the NFRC is the deterioration of fiber in the alkaline surrounding of OPC concrete [6,7]. Moreover, less greenhouse gas (GHG) emission, less energy consumption, and avoiding deficiency in binder quality makes SCMs an attractive option [8–12]. The use of by-products (slag, fly ash (FA), silica fume (SF), and other waste materials) as SCMs is an effective solution for mitigating air pollution, but the appropriate SCM for NFRC should cause a decrement in pore solution alkalinity in the binder. Since the resources for by-products as SCM are limited and may be challenging to approach in the near future, limestone-calcined clay cement (LC^3) is an alternative for a compatible binder for natural fibers. A review of the latest developments in SCMs (especially LC^3) and NFRC (specifically in combination with SCMs) are the goals of this paper.

2. Supplementary Cementitious Material (SCM)

Green buildings are essential elements for acquiring sustainability, and the concrete industry can move toward sustainability by introducing SCMs [13,14], which can also lead to improved durability and mechanical properties of concrete [15,16]. Industrial residues, such as SF and FA, are extensively employed as SCMs due to the high pozzolanic reactivity [16–19]. Furthermore, continuous effort is made to introduce agriculturally sourced pozzolanic substances, such as rice husk ash (RHA) [20,21], corn cob ash [22,23], wood ash [24], natural zeolite [4,25], bamboo leaf ash [26], and palm oil fuel ash [27–31]. As an example, when cement is replaced by micro-palm oil fuel ash (mPOFA) at certain levels, the compressive strength will be increased [32,33]. Replacing 10% weight of cement with mPOFA increases compressive strength up to 33%. This could be caused by mPOFA occupying the space between the particles of cement and enhancing the creation of calcium-silicate-hydrate (C-S-H) gel [34]. Table 1 expresses the composition and properties of typical OPC and some common SCMs. The higher value of SiO_2 and Al_2O_3 and Fe_2O_3 means the higher pozzolanic feature of SCM. According to ASTM C618, the value of all these three oxide compositions together should be more than 70%, as the requirement of material to be considered to be class N or F natural pozzolan.

FA is known as one of the most common SCMs which can reduce GHG emission of concrete and enhance durability, fracture toughness, and compressive strength of this material [13,42,43]. On the other hand, it is noted in previous studies that although enhancement in durability and compressive strength was observed by using FA, extensive usage may lead to challenges such as higher carbonation and delayed hydration [43]. Moreover, SF is the other commonly used pozzolanic substance that can also enhance the strength and durability significantly due to the high purity of silica content with fine particle size increasing its reactivity [35,41,44]. However, the main challenge for SCMs which are by-products of other industries (such as SF and FA) is the limitation in global production [45]. Furthermore, the quality of by-products is the other issue. For example, over 66% of the accessible FA, which has one of the highest quantities between these by-products, is not appropriate for mixing with cement [46].

Calcined clay is a kind of artificial pozzolan and its pozzolanic activity is affected by parameters such as the quantity of calcined minerals, impurity measure, activation technique, and post-calcination. [47]. Calcined clays appear as a confident source of SCM, able to offer a considerable replacement of the Portland cement clinker in mixed cement [48]. Various types of clay minerals include illite, kaolinite, palygorskite, and montmorillonite [49,50]. It is documented that among the different type of clay minerals, kaolinite has the highest pozzolanic activity [47,51]. After calcining the kaolinite-containing clay, metakaolin is created that is an amorphous alumino-silicate ($Al_2Si_2O_7$), which may make a reaction with calcium hydroxide to provide calcium-aluminate-silicate-hydrate (C-A-S-H) and aluminate hydrates [45]. Furthermore, carbo-aluminate hydrates could be produced as the reaction between the alumina and limestone [52]. The metakaolin (clay) is an abundant material and also its quality is further stable compared to FA and slag [53–56]. Mayo and Hassan reported that by the presence of 20% metakaolin in the self-compacting concrete mixture, the tensile and compressive strengths (28 days) could be increased to 25% and 30%, respectively [57]. This indicates that calcined clay has the potential to show higher pozzolanic reactivity than FA.

Table 1. Typical composition and properties of ordinary Portland cement (OPC), SF, FA, limestone, metakaolin and calcined clay [6,13,35–41].

Chemical Composition and Physical Properties	Ordinary Portland Cement	SF	FA	Limestone	Metakaolin	Calcined Clay (50.3 wt.% Kaolinite Content)
SiO_2 (%)	19.2–21.63	90–95	46.44–50.96	0.1–0.8	51.8–57.37	44.9
Al_2O_3 (%)	4.18–4.27	0.25–1.2	25.88–38.01	0.3	38.63–42.4	32.3
Fe_2O_3 (%)	3.32–3.45	0.15–1.3	3.12–8.25	0.3	0.77–4.15	15.4
TiO_2 (%)	—	—	1.36	—	1.07	2.4
CaO (%)	63.25–64.93	0.36–1.5	2.15–7.5	55–58	0.03–0.071	1.3
MgO (%)	1.61–2.77	0.47–2	0.23–2.60	1.8–0.2	0.07	0.8
Na_2O (%)	0.09	0.13–0.5	0.33–1.26	0.01–0.1	0.39	0.4
MnO (%)	—	0.02–0.07	—	—	—	0.1
K_2O (%)	0.78	0.2–0.84	0.88–2.65	0.01	0.218–0.49	0.2
SO_3 (%)	2.02–3.35	0.69	0.65–0.69	0.05	0.105–0.15	0.1
P_2O_5 (%)	0.09	0.04–0.17	0.06–0.35		0.61	0.4
Loss of ignition (%)	1.24–2.49	2.29–3	2.79–3.2	42.6–43.4	1.04	1.7
Specific gravity (g/cm^3)	3.2	1.9–2.15	2.14	—	2.59	—
Specific surface (cm^2/g)	3280–9000	2730	3640	18,000	—	45,700
Bulk density (kg/m^3)	—	300–660	—	—	—	—

Increase in compressive strength of mortar blending at an early age was also observed by using metakaolin as SCM [48,58,59]. Furthermore, combination of limestone and metakaolin resulted in higher compressive strength compared to using typical OPC [58]. Avet et al. stated that compressive strength of mortars containing different types of calcined clay appeared mainly dependent on the calcined kaolinite content irrespective to the other parameters [59]. Sulfate resistance is also reported to be significantly good for the investigated mortars with calcined clays (either calcined montmorillonite or metakaolin), non-dependent to the pore structures and compressive strength [48].

2.1. Limestone-Calcined Clay Cement (LC^3)

Among various SCMs available for substituting Portland cement clinker, the features of a ternary blend identified as LC^3 is evaluated broadly in terms of its benefits over OPC [45,52,59,60]. Calcination at temperatures between 600 and 800 °C results in the pozzolanic activity of kaolinite [50]. Limestone and kaolinitic clay are present in the earth crust abundantly, and much lower heating temperature compared to Portland cement clinker is required to produce calcined clay. Only 0.3 tons of CO_2 may be emitted for producing 1 ton of calcined clay [45,61], which is much less than the production of the same mass of OPC [62] (which is typically 1 ton of CO_2). There are many types of clay with different mineral composition depending on the region. Usually, most of clay types have about 40% kaolinite content or higher, which means they are suitable for calcination to produce highly reactive pozzolan. There are three common methods for calcination including rotary kilns, flash calcination and fluidized bed [56,63,64]. Therefore, LC^3 mixes have considerable variations in performance and color, based on the material source as well as calcination and use method. It is noteworthy that by substitution of clinker with limestone in LC^3 blends, both cost and the environmental impacts are reduced [45]. Optimal mechanical characteristics and enhancement in durability tests are observed with the replacement of 50% of clinker [45,52]. The viability of any technology depends on four key elements, including economic viability, technical feasibility, easy accessibility of raw materials and low capital investment. The developed LC[3] technology meets all the mentioned criteria [45]. One of the challenges with using limestone and calcined clay as SCM is the reduction in workability compared to the OPC binder. This issue could be managed by using the appropriate dosage of superplasticizer (SP) and also viscosity-modifying admixture (VMA) [56,64]. The relation between the dosage of SP and VMA with the content of calcined clay and limestone is still unformulated properly. There are many parameters related to the physical and chemical features of materials (e.g., particle size distribution, calcination temperature and chemical adsorption) and application of binder for getting the proper correlation and formula. Developing a chemical admixture designed for LC[3] mixes is still under demand.

2.1.1. Mechanical Properties of LC[3] Cement Binder

Antoni et al. and Avet et al. reported the highest compressive strength was found by the weight proportion of 1:2 for the limestone to metakaolin [52,59]. The most significant parameter of the calcined clay is kaolinitic content leading the mechanical properties of calcined clay-based binder systems. The comparable pozzolanic reactivity is also obtained by the lower levels of metakaolin in calcined clay (metakaolin content: 40–50%) which was confirmed by Avet et al. [59]. Moreover, Chen et al. showed an increase in the metakaolin content of calcined clay, increases the compressive strength (Figure 1). MIX-R in Figure 1 is the reference mixture with no calcined clay and MIX-L, MIX-M, and MIX-H contain low (40–50%), medium (62.5%), and high (75%) amounts of metakaolin content of calcined clay, respectively [65]. Moreover, recent studies indicate that improvement in mechanical and durability properties is significant even by introducing low or medium kaolinite content to the mix [59,66]. The LC[3] mortars with different kaolinite content (41.9%, 50.3%, 79.4% and 95.0%) indicated 9%, 9%, 27%, and 34% greater compressive strength compared to OPC mortar, respectively [66]. The results of previous studies introduce the LC[3] mixture as a promising ternary blend for improving the mechanical properties of concrete or mortar. Moreover, using calcine clay with low kaolinite content which is widely accessible seems to be an economical choice for the concrete industry. These statements are verified by other studies. [65,67].

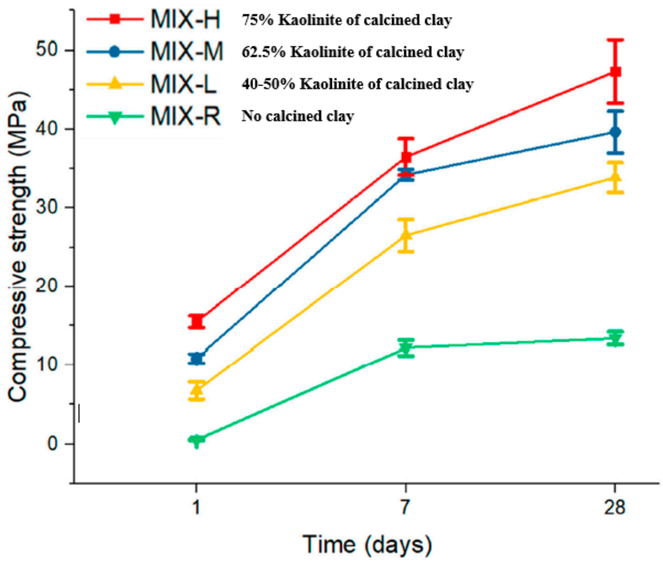

Figure 1. Compressive strength of concrete containing calcined clay with different metakaolin content [65].

2.1.2. Durability and Microstructure of LC[3] Cement Binder

In LC[3] technology, not only can the larger amount of OPC be replaced by SCMs to enhance the mechanical properties and reduce GHG emission, but also carbo-aluminate hydrates are generated, which can occupy the capillary pores [45]. Considerable incorporation of aluminum is discovered for LC^3 blends compared to the OPC and the C-A-S-H gel of LC^3 system shows significant variations in the composition. The kaolinite content of calcined clay has the main role of increasing the aluminum incorporation and its integration [39]. Furthermore, the chemical composition of calcium carbonate and alumina creates supplemental aluminate ferrite monosulfate (AFm) phases and stabilizes ettringite [52].

LC^3 has shown considerable improvement in chloride resistance of concrete compared to the other mixes with similar compressive strength [67,68]. This is mainly due to the creation of a large quantity of C-A-S-H and a synergetic impact between limestone and calcined clay [52,69]. Resistance against chloride ingress is tested by using high to intermediate grades of kaolinite content in clay and where it was found that chloride resistance of clay containing intermediate amount of kaolinite was in a similar range to high kaolinite content (which is an expensive choice) [66]. Furthermore, studies indicated that the chloride penetration in OPC mortar after two years of exposure was four times higher than the LC^3 mixtures (of 50% and higher kaolinite content) [66]. The main reason for this feature was ascribed to the denser structure of the LC^3 compared to OPC. The action against capillary water absorption and gas permeability indicates that LC^3 can provide significant performance in comparison to OPC. Moreover, using hydrophobic agents can lead to a material with considerably higher resistance to moisture ingress [70–74] meaning that LC^3 concrete has the potential to be exploited at environmental conditions where there is a risk of chloride ingress, including marine environments [67].

Furthermore, sulfate attack and Alkali–Silica Reaction (ASR) could both be mitigated by the LC^3 binder. A minimum quantity of limestone and calcined clay (around 30%) is reported to mitigate the sulfate attack [75]. Shi et al. suggested that LC^3 could be involved in standards as an innovative kind of sulfate-resisting Portland pozzolan cement [48].

3. Fiber-Reinforced Concrete (FRC)

Regardless of numerous benefits, concrete has some weaknesses including low energy-absorption capacity and low tensile resistance resulting in spalling, cracking, and lower lifespan of the structures [76,77]. Recently, using macro fibers as concrete reinforcement has become prevalent to present a solution for enhancing the mechanical properties of the OPC concrete [5,78–80]. The use of fiber in concrete matrix has less or no impact on concrete pre-cracking behavior. However, fibers improve post-cracking response, control the brittle fracture process, provide strength, and offer post-cracking toughness through the advantage of reliable deformation behavior and post-cracking strength [81–83]. Furthermore, incorporating fibers in cementitious substances has become important to some extent, because of reducing the shrinkage cracking, which is able to enhance the material durability. The preventing of shrinkage cracks may contribute to diminishing the material permeability [84]. When considering the structural behavior of a material, it is important to consider both strength and toughness together. The capacity of the material to absorb energy in the plastic range is considered to be the toughness index [83]. The propagation of the crack is inhibited by adding fibers to the concrete matrix, resulting in improvement of energy-absorption capacity [85–87]. The range of the enhancement in the mechanical properties and toughness index of concrete mixture depends on the fiber length and its amount [88–91].

Toughness index of FRC is increased by reduction in fiber cross-sectional area. Higher specific surface area is achieved by reduction in the diameter of the fibers, leading to higher contact areas between fibers and the matrix. Moreover, it causes a significant increment in FRC energy absorption compared to plain concrete [92]. In the mechanisms of energy-absorption in FRC, de-bonding and fiber pull-out are features related to the fiber surface area. Therefore, fiber-specific surface (FSS), the fiber content (FC), and the reinforcement area are relevant parameters to be investigated to find their effect on FRC properties. The implication is that the length of individual fibers influences computing the reinforcement area. To calculate these parameters, many analytical expressions are mentioned in reference [81].

Hasan et al. stated that the splitting tensile, compressive, and flexural strengths reached their maximum with 0.36% fiber volume fraction in comparison to plain concrete. The concrete strengths started to decrease due to high-volume fiber interface with the cohesiveness of the concrete matrix causing difficulty in concrete compaction lowering its workability [93].

According to past scientific findings, short fiber reinforcement in concrete could enhance the properties of plain concrete in the appropriate fiber volume fraction. Presently, regarding financial problems and environmental concerns, natural fibers are fascinating for industrial applications. Therefore, the natural (bio) fiber-reinforced concrete (NFRC) is an attractive subject for further research.

3.1. Natural-Fiber-Reinforced Concrete (NFRC)

Recently, many studies have considered bio-fibers for reinforcement of Portland cement-based concrete structures to increase the tensile strength, flexural strength, tensile ductility, and flexural toughness, reducing the drying shrinkage and density of concrete [94–99]. The benefits of NFRC, such as incremented toughness, improved cracking behavior, greater durability, and enhanced impact resistance and fatigue were well demonstrated formerly [91,97,100–102]. Also, research outcome has shown NFRC possesses the potential for repairing, retrofitting, and rehabilitation of reinforced concrete structures and as a new construction material [103].

3.1.1. Mechanical Properties of NFRC

In terms of impact resistance, Zhou et al. [104] and Wang et al. [105] reported the positive effects of the impact resistance of concrete reinforced by jute fiber and hybrid bamboo-steel fiber, respectively. More results on impact energy absorption of NFRC slabs were reported by Ramakrishna and Sundararajan [101]. Investigations of jute FRC show that compressive strength is not considerably influenced by adding fibers; however, flexural, tensile strengths and toughness are all considerably incremented [91]. Moreover, it is stated that the modulus of elasticity, compressive strength, and repetitive impact resistance of coconut FRC (CFRC) were reduced by increasing the length of the fiber [106]. Also, a similar finding reported that the short flax fiber (12 mm) had the most effects on the flexural strength of flax FRC [107]. Al-Oraimi and Seibi tested many FRC samples by using the different FC of glass and palm trees. They stated that adding fibers, in general, improves the toughness of concrete and enhances its impact resistance; also, bio-fibers are comparable to the synthetic fibers in improving the toughness and impact resistance [83]. Moreover, from another study, hemp fibers improve the concrete fracture energy for 70% in NFRC. By bridging the cracks, fibers provide a post-cracking ductility, leading to significant improvement of toughness [102]. Furthermore, higher flexural strength is exhibited by alkaline treatment of hemp fibers compared to their non-treated equivalents [7].

3.1.2. Durability of Bio Fiber-Reinforced Concrete

Degradation of natural fibers are investigated by treatment in aging environments [108–114]. Pretreatment of natural fibers is a well-documented method to enhance the degradation resistance. Silane coating [115,116], out-of-autoclave method [117], hornification [118], sodium silicate [119], potassium silicate [119], alkaline treatment [115,120], and coating fibers with bacterial nano-cellulose [121] were used to enhance the durability and mechanical characteristics of NFRC by creating protective layers on the fiber surface or enhancing cellulose structure of natural fiber.

The other method for increasing the durability of natural fibers is use of appropriate SCMs in the concrete matrix. The lignin quantity of natural fiber has a main role in the sensitivity of NFRC to natural weathering. This is caused by the more susceptibility of hemicelluloses and lignin to chemical deterioration and alkaline environment of cement. The findings show that by combining the calcined clay minerals, alkalinity of pore solution is decreased which can lead to mitigating fiber deterioration. Both alkali hydrolysis and mineralization of natural fiber can be alleviated significantly by this technique [6]. Different studies agree that decreasing the alkalinity of the matrix using SCMs as cement replacement can prevent the chemical attack to lignocellulosic fibers in the matrix [6,7,110,111,122–125].

The rate of natural fiber deterioration in cementitious materials could be reduced by using some SCMs such as nano-calcined clay [7]. Hakamy et al. stated that the substitution of cement with 1 wt.% nano-calcined clay results in not only enhancing the microstructure but also facilitating the pozzolanic activity which results in stronger bonds between the matrix and the surface of treated hemp fibers [7]. Furthermore, initial flexural strength as well as durability of NFRC are improved by the coupled replacement of metakaolin and montmorillonite, due to modifying the mineralization and alkaline degradation of the fibers. For example, the degradation of sisal fibers was moderated most considerably at high cement substitution level (about 50%) [6]. Using short-length natural fibers and the effects of cement and SCMs on fiber degradation is well documented [6,7,75,111]. Moreover, incorporating a pozzolanic substance into the matrix results in a considerable reduction in capillary absorption and chloride penetration. Overall, the use of appropriate amount and quality of SCMs can enhance the mechanical and durability properties of FRC [84]. Table 2 shows the effect of SCMs on the mechanical performance of natural fiber cementitious composites. Future studies need to be conducted on the adjustment of the mix design, assessing the long-term performance and standardization of the natural-fiber-reinforced LC^3 concrete.

Table 2. The effect of SCMs on the natural fiber performance in cementitious binder.

Name of Natural Fiber + SCM	Deteriorating Environment	Duration	Type of Mechanical Properties	Percentage of Changes Compared to Conventional Concrete	Notes	Reference
Sisal fiber	Alkaline solution	28 days of immersion	Impact strength	About−2%	The impact strength of 2% sisal NFRC was about 2 times more than plain mortar.	[114]
Sisal fiber + 30% SF	Water bath (Alkalinity of binder)	730 days of aging	Flexural strength	+28%	The flexural strength increased after aging period due to using 30% SF.	[111]
Sisal fiber	Outdoors	322 days	Flexural strength	−70%	The first crack strength increased by about 53% due to the use of sisal fiber.	[108]
Sisal fiber + 45% MK + 5% montmorillonite	Wetting and drawing cycle	30 cycles	Tensile strength of fiber embedded	+500%	The positive effects of MK on the mitigation of alkalinity was proved.	[6]
Hemp fiber + 1% calcined Nano clay	N/A	N/A	Flexural strength	+38%	——	[7]
Coir fiber	Sulfate attack	2 years of immersion	Compressive strength	−14%	The deterioration value for conventional concrete was 54%.	[112]
Sugarcane fiber	Sulfate attack	2 years of immersion	Compressive strength	−20%	The deterioration value for conventional concrete was 54%.	[112]
Coir fiber	Freezing and thawing	300 cycles	Modulus of elasticity	−10%	The deterioration value for conventional concrete was 8%.	[112]
Sugarcane fiber	Freezing and thawing	300 cycles	Modulus of elasticity	−14%	The deterioration value for conventional concrete was 8%.	[112]

3.2. *Kenaf Fiber-Reinforced Concrete (KFRC)*

The kenaf plant is able to grow to heights of 3.5–4.5 m within 4–5 months [126]. Studies indicate that the kenaf plant had the optimal CO_2 absorption among the investigated plants. Kenaf plant can absorb 1.5 times the carbon dioxide by its weight [127]. The findings show that the tensile strength of kenaf fibers vary between 223 MPa and 1191 MPa and the elastic modulus and final tensile strain of the kenaf fiber vary within 2860 MPa to 60,000 MPa and 0.012 to 0.1, respectively [120]. Kenaf fiber shows a linear stress–strain diagram [120,128]. Currently, kenaf fiber is used in bio-materials with a wide application area [94,129–132]. Table 3 presents the mechanical properties of some natural fibers.

The elastic modulus of some natural fibers such as hemp, kenaf, and flax are comparable to glass fibers, while the density of these natural fibers is one half the density of glass fiber. According to the nature of bio-fibers, the properties may differ in different origins, so the range of properties are reported in the following table.

Table 3. Mechanical properties of natural fiber.

Fiber	Elastic Modulus (GPa)	Tensile Strength (MPa)	Elongation at Break (%)	Density (g/cm^3)	Reference (s)
Kenaf	40	731.64	1.8	1.2	[120,129]
Jute	26.5	393–773	1.5–1.8	1.3	[133]
Sisal	9–22	400–700	2.0–2.5	1.43–1.5	[134,135]
Flax	27.6–65.5	345–1500	1.86–3.2	1.5	[107,136]
Hemp	70	690	1.6–4.0	1.47	[136–138]
Pineapple	34.5–82.5	170–1627	1–3	1.44–1.56	[139–141]
Cotton	5.5–12.6	400	7.0–8.0	1.5–1.6	[140]
Oil Palm	0.48–9	24.9–550	4–18	0.7–1.55	[142,143]
E–glass	70–71	2000–3500	0.5–3.4	2.5–2.55	[120,137,144]
Carbon	224–240	2650–4000	1.4–1.8	1.4–1.75	[145,146]

Surface treatment of kenaf fibers by sodium hydroxide (NaOH) can reduce its hydrophilic properties [120]. This reduction in the fiber water sorption characteristic causes an improvement of fiber durability and reduces its biodegradability [147]; however, it may affect the bond strength with the cementitious matrix.

According to the literature, higher toughness is exhibited by NFRC (such as KFRC) generally compared to the normal concrete [94,104,124]. Also, microstructural analysis by scanning electron microscopy (SEM) shows a good bonding between the kenaf fibers and concrete matrix [124]. Lam and Yatim conducted research on KFRC by changing the fiber volume content and the fiber length. They stated the indirect tensile and flexural strength increased by an increment of FC and fiber length [94]. This statement seems to be in contrast with the previous statement about coconut FRC in terms of the effects of fiber length [106] but both studies suggested that the 50 mm fiber length was suitable. Moreover, the ductile failure mode was observed compared to plain concrete, which resulted in an enhancement in cracking behavior and ductility. Moreover, another study reported a toughness index in KFRC almost 3 times higher than the OPC concrete control samples [124]. Use of natural fibers such as kenaf fiber to cast NFRC (specifically KFRC) can result in not only economic profit in terms of production cost and material weight, but also in terms of health benefits for society when compared to synthetic fibers [104,147]. The green concrete developed has an environmental benefit which is of immense importance in the present context of the sustainability of natural resources [127,147]. Moreover, the quantity of CO_2 would be reduced in the atmosphere by using kenaf fibers in concrete. It may decline the high CO_2 released within the manufacturing of Portland cement. Thus, kenaf fiber-reinforced concrete (KFRC) is a potential green material for various construction purposes [94,124].

4. Discussion and Conclusions

Using natural fibers as an alternative for concrete reinforcement is of interest not only due to increasing ductility and versatility of the material but also from an environmental perspective. On the other hand, the binder needs to be compatible with the fibers and be environmentally friendly to make a favorable composition. SCMs including SF, FA, slag, and LC^3 can enhance mechanical and durability properties, reduce the environmental impacts, and adjust the alkaline environment and pore structure of the matrix. The latter can be of interest when dealing with the durability of nature-based materials into concrete. While resources for SCM materials which are industrial by/products are limited and may be challenging to approach in the near future, LC^3 can be an available choice in most parts of the world. Furthermore, the clay can be calcined by using renewable energy which can lead to zero emissions for the calcination process. The weight proportion of calcined clay to limestone as 2:1 and the cement replacement ratio of 50% are reported to be optimal for normal uses in different studies.

The kaolinite content of the clay, which is reported to play an important role in cementitious functionality of calcined clay, varies significantly in different types of clay. However, studies have shown that calcined clay with low or medium kaolinite content can also be used in LC^3 achieving acceptable mechanical properties for common applications. This means the LC^3 is not sensitive to kaolinite concentration and different types of clay available with minimum transport can be suitable for concrete production leading to reduction in cost and environmental impacts. Furthermore, improvement in durability properties in terms of chloride resistance, ASR, and sulfate attack are reported for LC^3 concrete with medium kaolinite content in the clay.

On the other hand, the performance of kenaf fibers as short-length natural fiber concrete mixture is investigated in different studies mainly using OPC. Mechanical properties of concrete such as toughness, tensile strength, and impact resistance can be improved using this type of fiber. Moreover, durability properties such as carbonation, sulfate, and chloride resistance were reported to be enhanced compared to OPC concrete. Natural fiber volume content under 1% and fiber length of about 50 mm are reported to be a proper performance in the concrete mix.

Combination of LC^3 with natural fibers such as kenaf fiber can be a promising composition to get green concrete with low GHG emission and energy consumption due to the replacement of cement by LC^3 as well as significant properties of kenaf plant in absorbing the CO_2 from the air and introducing proper fibers for concrete mix. Current studies on this composition are limited and need to be taken into account for further investigation. Furthermore, adjustment of the mix design, assessing the long-term performance, as well as standardization, are the next steps for use of the kenaf fiber-reinforced LC^3 concrete in practice.

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