fibers

Review

Kenaf Fibre Reinforced Cementitious Composites

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Abstract: Increased environmental awareness and the demand for sustainable materials have promoted the use of more renewable and eco-friendly resources like natural fibre as reinforcement in the building industry. Among various types of natural fibres, kenaf has been widely planted in the past few years, however, it hasn't been extensively used as a construction material. Kenaf bast fibre is a high tensile strength fibre, lightweight and cost-effective, offering a potential alternative for reinforcement in construction applications. To encourage its use, it's essential to understand how kenaf fibre's properties affect the performance of cement-based composites. Hence, the effects of KF on the properties of cementitious composites in the fresh and hardened states have been discussed. The current state-of-art of Kenaf Fibre Reinforced Cement Composite (KFRCC) and its different applications are presented for the reader to explore. This review confirmed the improvement of tensile and flexural strengths of cementitious composites with the inclusion of the appropriate content and length of kenaf fibres. However, more studies are necessary to understand the overall impact of kenaf fibres on the compressive strength and durability properties of cementitious composites.

Keywords: fibre; kenaf fibre; cementitious composites; mechanical properties; durability properties

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1. Introduction

The sustainability target is to keep lives on our planet for the foreseeable future by adequate care and support of the current activities without damaging the ecological balance. Sustainability depends on three factors: society, economy and environment. Sustainable development must take care of these factors wisely to maintain biodiversity and equilibrium in the ecosystem [1]. Clean, high-performance and durable construction materials are becoming the main interest of sustainable buildings all around the world [2].

Cementitious composites like grout, mortar, concrete, etc. are the most widely utilized building materials for a variety of infrastructure projects around the world, which require high ductility and energy absorption capacity for a variety of applications such as bridge decks, highway pavement and industrial building floors. However, cementitious composites have low tensile strength, poor ductility, low cracking resistance and little energy absorption [3]. Internal micro-cracks are inherently existent in the cementitious composite, and its low tensile strength is owing to their propagation, possibly resulting in a brittle failure of the composite. Accordingly, improving the toughness of the cementitious composites and reducing the size and probability of weaknesses will result in a better performance.

One way of improving the cementitious composite is by introducing fibres. It was discovered that adding steel, synthetic and natural fibres to the cementitious mixture is effective in bridging cracks, transferring loads, and enhancing the dispersal system of micro-cracks. The fibres behave as crack arresters and greatly enhance the cementitious composite properties, not only under tensile and flexural loads [4] but also under shrinkage cracking [5], chemical attacks [6] and impact blows [7].

Recently, due to the rising use of natural fibres and the necessity to satiate their demand for composites, Kenaf Fibres (KF) gained much popularity, which resulted in the establishment of kenaf as an industrial crop worldwide [8]. Despite the numerous benefits associated with utilizing KF, they have high water and moisture absorption capacity, which is a problem that must be addressed before they can be incorporated in cementitious composites. In addition, KF are made up of hemicellulose, lignin, pectin and impurities. These substances might delay cement hydration by generating a protective layer around partially hydrated cement grains or form a chelate complex with the cations found in hydrated cement [9]. KFs' amorphous components (hemicellulose, lignin, and impurities) are also susceptible to Ca $(OH)_2$ solution and can degrade quickly in an alkaline environment. The degradation of these amorphous elements can produce saccharides, which can slow down cement hydration [10]. Furthermore, impurities on the surface of the fibre inhibit interlocking with cementitious materials, which affects the mechanical properties of the fibre reinforced cementitious materials. Therefore, in order to fully exploit the properties of KF, it is necessary to modify them before using in cementitious materials. Fibre pre-treatment is an effective method to overcome these weaknesses. Although the treatment may increase the cost, nevertheless, obtaining sufficient bond strength and subsequently improving the composite is worth the extra cost.

By using the keyword search comprised of the search strings "kenaf fiber" or "kenaf fibre" and "application" or "composites" in the ScienceDirect database, it's obvious that the number of published papers on the subject has increased in the last decade, as demonstrated in Figure 1. The justification for this acceptance is mostly due to the superior properties of this fibre, as shown in Figure 2. For example, the kenaf plant has rapid growth abilities, which allows it to produce a great volume of raw materials in a short period at a low cost. Natural fibres, like KF, are considerably cheaper than other fibre types like carbon and glass fibres. Kenaf fibre costs 0.53 US$ per kg while the price of carbon and glass fibres are 500 US$ and 3.25 US$ per kg, respectively [11]. Furthermore, compared to the other types of natural fibres, KF absorb the highest level of carbon dioxide (CO_2), possess low density, and requires low production energy [12]. The amount of energy required to produce 1 kg of kenaf fibres is around 15 moles per joule, which is lower than the 54 moles per joule required to produce the same quantity of glass fibres [11]. Also, kenaf bast fibre has been identified as a potential reinforcing material in composites due to its high mechanical properties. A single kenaf fibre of 10 mm length and 83.24 μm diameter can achieve a tensile strength of 423 MPa [9].

Pirmohammad et al. [13] reported that KF have a great potential to replace glass fibres (GF). However, in comparison to GF, KF have not been widely used for large-scale structural applications due to the lack of understanding and studies related to their effects on the performance of cement-based composites. As a result, the purpose of this work is to review the current literature on the effects of KF on the properties of the cementitious composite. The properties of KF and kenaf fibre-reinforced cement composites (KFRCC) addressed in this article are shown in Figure 3. Potential solutions have also been proposed in areas where KF have exhibited a negative impact on the performance of the cementitious composite. This review is expected to be a good reference to scientists, engineers and other people interested in using this environmentally friendly material to improve the performance of cement-based composites. More studies and development on the application and understanding of KFRCC is also hoped to result from this work.

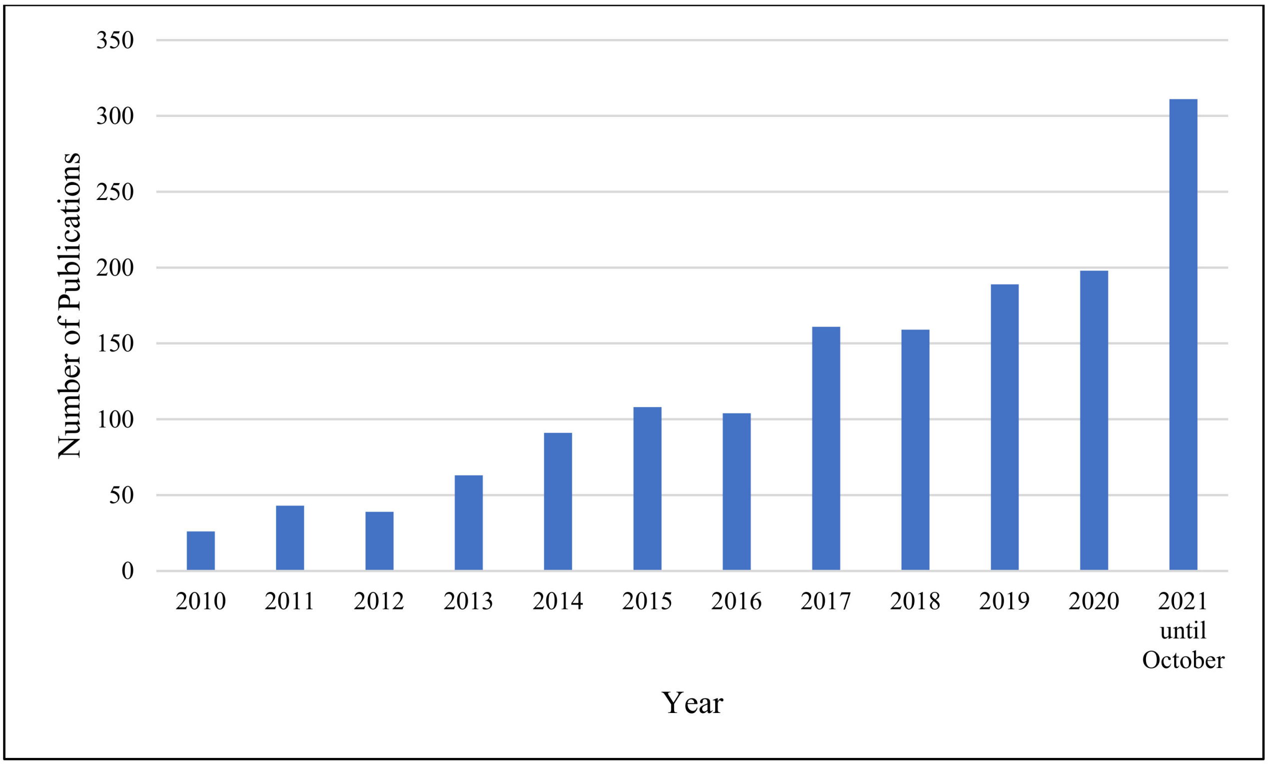

Figure 1. Scientific publications on KF (data from ScienceDirect).

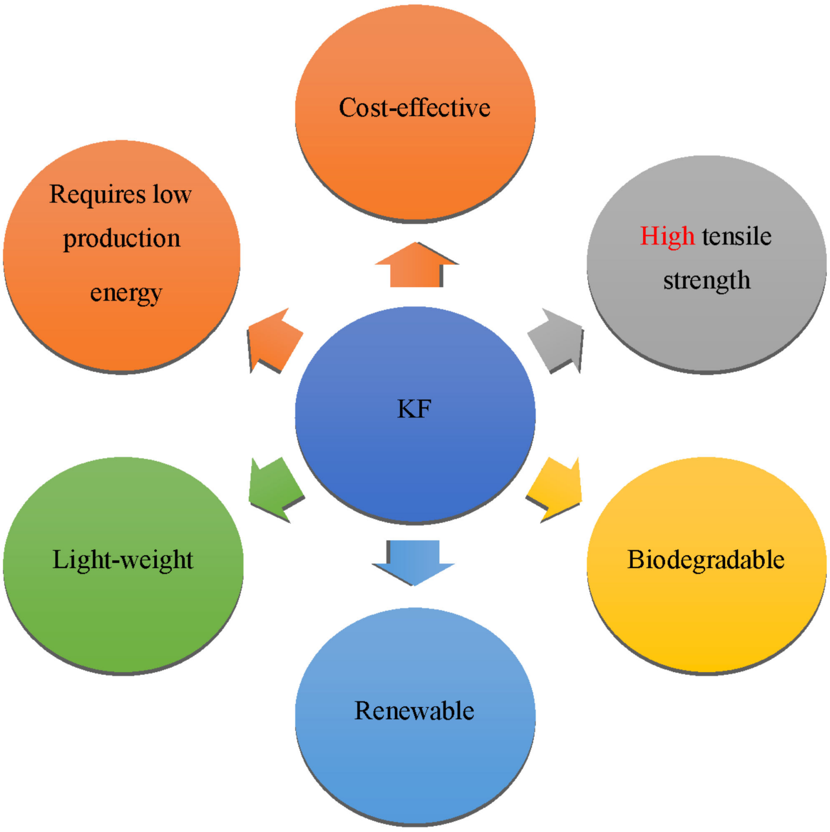

Figure 2. A schematic depicting the usefulness of KF in sustainable constructions.

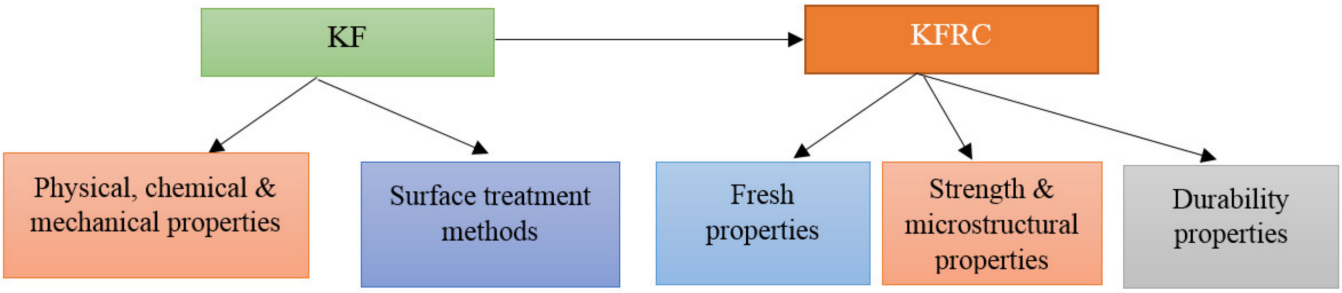

Figure 3. A schematic depicting the properties of KF and KFRCC which will be discussed in this review.

2. Kenaf Plant and Fibre

Kenaf is a dicotyledonous plant, over 4000 years old and belongs to the hibiscus family, which also includes jute and okra (Figure 4). It originated in Africa, but India and China produce more than 70% of the world's kenaf, making it the major source of bast fibre in these countries [14]. Kenaf is produced in more than 20 countries, with a total output of 216,200 tonnes of kenaf and related fibres in 2014/2015 [15]. The Malaysian government has identified kenaf as a fibre crop with potential for economic growth and has established the National Kenaf and Tobacco Board to promote the fibre industry's growth.

Figure 4. (**a**) stem; (**b**) leaves; (**c**) flower; (**d**) seed. Reprinted from [14] with permission from Elsevier.

Kenaf plant is a well-recognized cellulosic fibre resource with both ecological and economic benefits. It grows to 1.5–4 m high within 4–5 months; thus, when used in a composite, its fast growth ensures that its availability and manufacturing costs are not problematic. Also, its lengthy stem can produce long fibres, which is an attractive character of plants [16]. It is a strong plant with a fibrous stalk that has high resistance towards insect attack and can be grown and adapted in various soils types and climate conditions with only a few chemical cares [17].

Kenaf plant is primarily cultivated for its fibres. The quality of extracted fibre is determined by the extraction process. Kenaf fibre harvesting and extraction have always been dependent on location, method of processing, equipment, and functions of the final products [18]. Kenaf is harvested in the winter, when the plants are still in the field, leafless, and the stem has been degraded by the climate.

Harvesting can be accomplished by hand or mechanically with specific farm equipment [19]. Kenaf has been hand-harvested for use as a cordage crop for the last 6000 years when it was first cultivated. The tall, cylindrical stalks are cut by using a curved blade or machete at or near ground level when hand-harvested. This method is time-consuming and involves human labour. On the other hand, the harvesting by using Kenaf Whole Stalk Harvesters can be achieved through few steps which start with pulling and windrowing, followed by retting, and finally balling parallel stalks.

After harvesting, the bark is removed from the stem and turned into fibre in a process called retting. Retting is a process that occurs as a result of the combined action of bacteria and weathering, allowing the stem material around the fibre bundles to degrade. The four types of retting currently in use are—biological retting (dew retting, water retting, enzyme retting), mechanical retting (using a decorticator), chemical retting, and physical retting [20]. Kenaf plant produces about 6–10 tons of dry fibre in an acre annually, which is equal to 4 times what the pine trees produce. Besides, up to 40% of kenaf stalk produces useable fibres, which is almost twice as much as hemp, flax, or jute [8,21].

2.1. Physical, Chemical and Mechanical Properties of Kenaf Fibre

The kenaf fibres are extracted from the plant's stalk, which is made up of two main parts. The outer part consists of long fibres called the bast fibre that makes up about 35% of the total weight of the plant, and the inner part is the core, which is a woody component with short fibres [16]. Bast fibres have a hollow centre channel or lumen that transports water and nutrients throughout the plant. The cell wall is composed of several layers: the middle lamella, the primary wall and secondary walls, which are divided into three categories: external secondary wall (S1), middle secondary wall (S2), and internal secondary wall (S3). These layers are made up of microfibrils that are orientated in space at specific (angles) depending on the layer. The middle lamella consists of pectin that cements fibres together into a bundle, while the primary cell wall is composed primarily of cellulose fibrils that are disorganized and embedded in a matrix of hemicellulose, lignin, pectin, and proteins. The secondary cell wall, which contains the most cellulose, is composed of three layers of cellulose fibrils with different axial orientations bound by hemicellulose and lignin [22–24]. The typical structure of natural fibres is presented in Figure 5.

Ashori et al. [26] studied morphology and chemical characteristics of both core and bast fibres. SEM images indicated that the bast fibre was thin and long, while the core fibre was wide and short. The chemical composition of the two fibre types was significantly different, as shown in Table 1. Since cellulose is responsible for the strength and stiffness of the fibre, it's clear that bast fibres have higher strength compared to the core fibres, making them more favourable as reinforcement material in composites.

Kenaf fibres change their features as the moisture content changes since the cell wall comprise hydroxyl groups that absorb moisture from the surrounding environment by hydrogen bonding. The hemicellulose components are primarily responsible for moisture attracting, while the cellulose, lignin and other components also have their roles [8]. The fibres' mechanical characteristics are influenced by where they are extracted from in the stalk. Fibres derived from the mid of the stalk, for instance, are stronger and more rigid than those derived from the end of the stalk, which is exposed to environmental factors and insect damage [17].

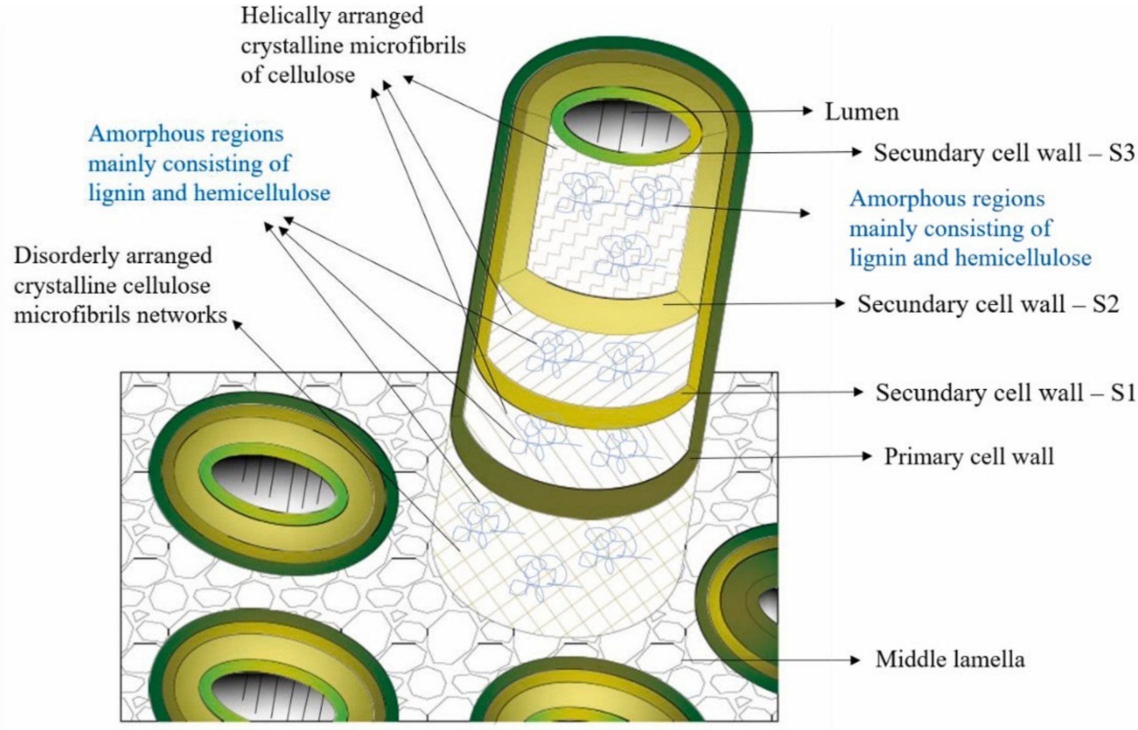

Figure 5. Structure of natural fibre. Reprinted from [25] with permission from Elsevier.

Table 1. Chemical composition of KF [26].

Type	Cellulose	Hemi-Cellulose	Lignin	Pentosan	1% NaOH Extract	Hot Water	E.B. Extract	Ash
Bast	56.4	26.2	14.7	13.5	14.5	3.4	2.7	2.2
Core	46.1	29.7	22.1	20.7	20.6	3.9	2.2	1.6

Table 2 summarizes the properties of KF based on several research investigations. The values acquired by researchers are not identical, as shown in Table 2. This may be attributed to the variance in KF utilized in terms of the place of origin, the weather condition and the quality of the initial retting process. Another reason for the variation is the large number of sub-species studied under the name kenaf [17].

Table 2. Collated characteristics of kenaf fibre.

Density (g/cm^3)	Tensile Strength (MPa)	Young Modulus (GPa)	Elongation at Break (%)	Ref.
1.45	930	53	1.5	[12]
1.29	157–600	12.8–34.2	-	[17]
-	129.10–267.69	9.02–11.88	1.35–2.07	[27]
1.4	223–930	14.5-53	1.5–2.7	[28]
1.2	580–925	-	1.26–2.6	[29]
1.2	350–600	40	2.5–3.5	[30]

2.2. Surface Modification of Kenaf Fibre

The major obstacles to using kenaf fibres as a reinforcement in composites are high water absorption capability, low durability and poor fibre-matrix adhesion. These are due to the presence of hemicellulose, lignin and pectin in their composition, which gives rise to hydrophilic properties that cause them to be less compatible in their interaction with hydrophobic matrices. As a result, a weak bond between the fibres and matrices are developed. Figure 6 shows how natural fibres' high moisture absorption reduces composites' overall mechanical performance. The absorption of moisture and the lack of interfacial bonding makes kenaf fibre composites less effective in transferring stresses and have lower durability [31].

To overcome these weaknesses, surface pre-treatment using chemical or physical modification has been identified as an effective method for reducing the water absorption of these fibres and for enhancing the interfacial adhesion between the fibre surface and the cement matrix [32]. Several chemical and physical modification methods have been discussed in the previous studies, which have accomplished different levels of success in enhancing KF properties and fibre-matrix bonding. Figure 7 displays the description, types, advantages, and disadvantages of these two methods.

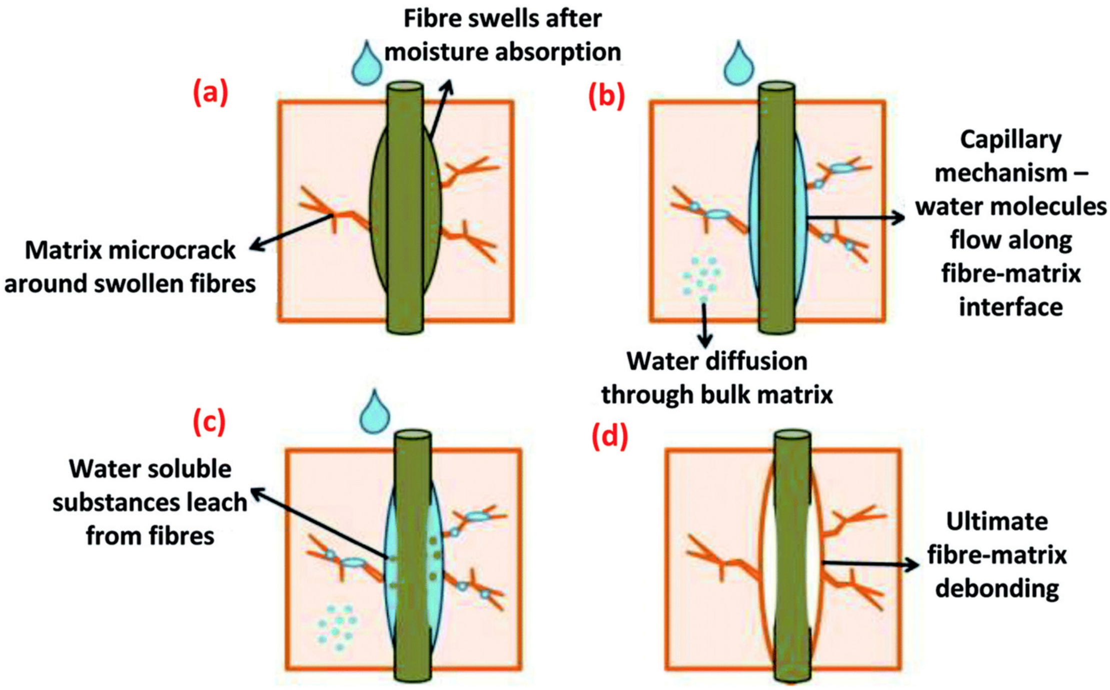

Figure 6. Effect of water on fibre–matrix interface. Reprinted from [33] with permission from Elsevier.

Table 3 summarizes the reported researches on KFRCC that focused on the modification of the KF. By comparing the treatment methods used in the publications on KFRCC with the treatment methods mentioned in Figure 7, it is clear that very few methods have been used to treat the fibres utilized in the KFRCC. Therefore, studies that dealt with the effect of various treating methods on the properties of the single fibres or other kenaf-composites have been mentioned to evaluate the effect of these methods on the properties of the composites and to encourage other researchers to examine the influence of these methods on the KFRCC, since it might improve the mechanical and durability properties of the cementitious composites.

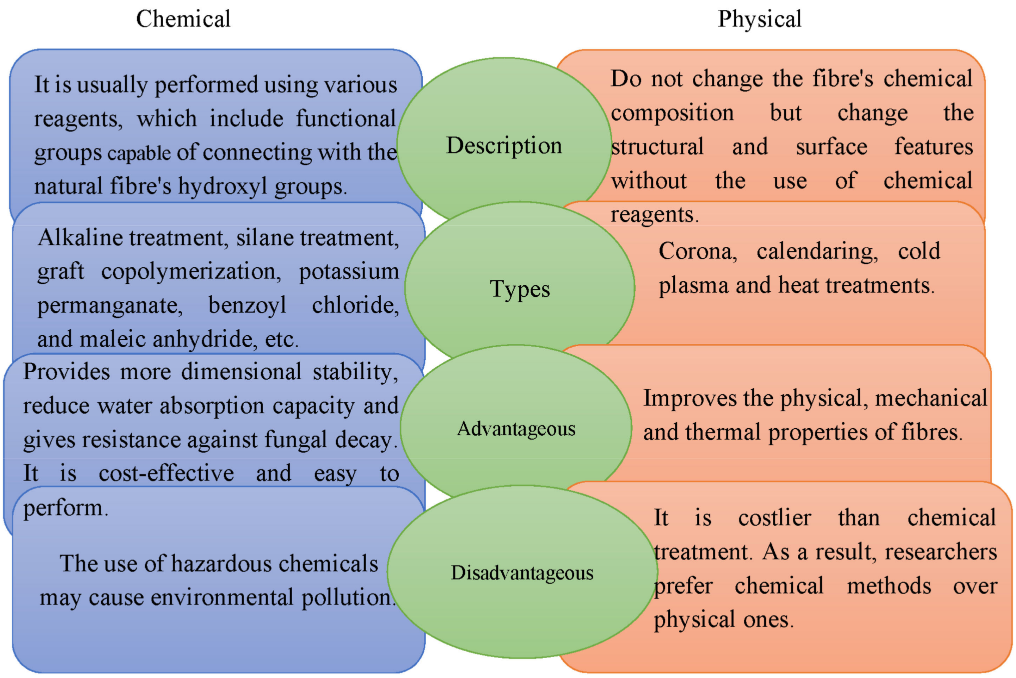

Figure 7. Fibres surface modification methods [8,11,34].

Table 3. The treatment methods applied on KF and their effects on the fibre's properties and their composites.

Treatment Method	Treatment Effect	Matrix	Tensile Strength (MPa)		Ref.
			Untreated	Treated	
	Improved the properties of the single fibres and the composite.	Cement	423 423	433 503	[9]
Alkaline treatment	Cleaned and chemically modified the surface of the KF, resulting in a rise in surface roughness, which improves interfacial adhesion between the cement matrix and KF in terms of hydration, and internal curing.	Cement	-		[21]
	Improved the tensile behaviour of the treated fibres.	Single	129.10	267.69	[27]
	Removed the lignin and hemicellulose components of KF.	Cement	-	-	[35]
	-	Cement	-	-	[36]
	-	Cement	-	-	[37]
	Removed the surface impurities of the fibres.	Single fibre	218	254	[38]
	Removed the impurities from the surface of the fibres and improved the mechanical properties of the composite.	Polyester	69.1	90.8	[39]
	Cleaned and chemically modified the fibre surface with increased surface roughness.	Single fibre	215.4	243.7	[40]
	Removed the amorphous hemicellulose and lignin from the fibre and re-arranged the cellulose chain into a more compact manner, resulting in an increased packing density and improved mechanical properties.	Single fibre	251.4	384.7	[41]
	Improved the mechanical strength of the composite.	Unsaturated polyester	67	84.2	[42]

Table 3. *Cont.*

Treatment Method	Treatment Effect	Matrix	Tensile Strength (MPa)		Ref.
			Untreated	Treated	
Silane treatment	Removed a large portion of hemicellulose, lignin, and hydroxyl groups, which improved the fibre-matrix interfacial bonding.	Phenolic	48	52	[43]
	Improved the flexural, interfacial shear strengths, and mechanical properties of the composites.	Thermoplastic polypropylene	26	47	[44]
		Thermosetting unsaturated polyester	43	85	
Graft copolymerization	Decreased the lignin content from 14.3% to as low as 3.3%. Besides, the SEM results showed that the treated KF surface was cleaner and smoother than the surface of the untreated fibres.	Single fibre	-	-	[45]
Hydrogen peroxide	Increased the cellulose content and the crystallinity of the fibres by 40% and 26.8%, respectively.	Single fibre	423.01	503.02	[34]
Potassium permanganate	Increased the cellulose content in the fibres by 21%, while the hemicellulose and lignin content decreased by 34.21% and 17%, respectively, compared to untreated fibres.	Single fibre	423.01	425	[34]
Benzoyl chloride	Improved the fibre-matrix interfacial adhesion by the formation of a new linkage that connected the surface of KF with the matrix.	polyvinyl chloride with epoxidized natural rubber	4.4	4.7	[46]
Stearic acid	Increased the matrix interphase region and wettability. Besides, increased surface roughness resulted in improved surface interaction between resin and fibre.	Unsaturated polyester	35.664	56.893	[47]
Heat treatment	Decreased the fibre surface moisture absorption and voids content, which resulted in a composite with better properties.	Thermosetting unsaturated polyester	-	-	[48]
	Increased cellulose crystallinity due to the modification of the molecular structure in addition to the partial removal of the impurities on the surface of the fibres.	Single	251.43	320.85	[49]

Almost all the treatment methods positively affect the properties of the single fibres and their composites, as presented in Table 3. The improvement is due to the removal of the impurities and some of the water-absorbing chemical components such as lignin, hemicellulose, wax and oils from the external surface of the fibres, besides increasing the surface roughness, which can enhance the bonding with the matrix.

By reviewing the published papers related to the KFRCC, it was found that only a few papers have paid attention to the effect of the treatment method on the properties of KFRCC [9,21]. Most of the studies only examined the effect of the pre-treated fibres on the properties of cementitious composites. Moreover, almost all of the studies used the alkaline treatment method for pretreating the KF. However, the studies related to employing KF in other kinds of composites such as polymer composites and even single kenaf fibres showed that the treatment method has a huge impact on the properties of both fibres and composite. Therefore, there is a need to examine the effect of the other treatment methods on the KFRCC properties.

3. Performance of Kenaf Fibre-Reinforced Cementitious Composites (KFRCC)

One aim of utilizing fibres is to overcome the brittleness of the cementitious matrix by affecting cracking behaviour, controlling the brittle fracture process, and providing strength and toughness after cracking. Fibres have the ability to bridge across the cracks and control their propagation. Fibre reinforcements could be classified by differences in types (synthetic, steel and natural fibres), aspect ratio (length of fibres divided by their diameter), geometry, volume fraction and mechanical properties [50].

This review aimed to determine the impacts of kenaf fibre reinforcement on the characteristics of cement-based composites. It covers studies done between 2010 to 2021. The initial keyword search comprised of the search strings "kenaf fibres" and "cement". The performance of KFRCC has been determined using a variety of testing methods. Many variables can influence the performance of these composites. The most frequent variables examined are the fibre type, length and content of KF. The fresh, mechanical, microstructural and durability properties are the most frequent dependent variables. The summary of studies related to KFRCC is shown in Table 4.

Table 4. Published studies related to KFRCC, covering different variables.

Ref.	Year	Fibre Diameter µm	Fibre Length mm	Optimum Length	Fibre Volume %	Optimum Volume	Testing Variables	Dependent Variables	Testing Method
[9]	2021	62.99–83.24	10	-	0.25–0.75	-	Treatment method, fibres content and effect of super-plasticizer	Mechanical properties	Compressive strength, modulus of elasticity and flexural strength and toughness
								Microstructural properties	SEM
[17]	2011		Mix (25–38)	-	1.2–2.4	1.2	Effect of fibre content	Mechanical properties	Compressive strength, elastic modulus, tensile and flexural strength
[35]	2015	-	25 and 50	50	0.5–2	0.75	Effect of fibre content and length	Fresh properties	Slump
								Mechanical properties	Compressive, tensile and flexural strength
[36]	2018	-	25 and 50	25	0.5–1.5	0.5–1	Effect of fibre content and length	Fresh properties	Slump
								Mechanical properties	Compressive, tensile and flexural strength
								Microstructural properties	SEM and EDX
[37]	2018	39–115	25 and 50	50	0.5–1	0.5	Effect of fibre content and length	Fresh properties	Slump, compaction factor and VeBe test
								Mechanical properties	Compressive, tensile and flexural strength and elastic modulus test
								Durability properties	Drying shrinkage

Table 4. *Cont.*

Ref.	Year	Fibre Diameter µm	Fibre Length mm	Optimum Length	Fibre Volume %	Optimum Volume	Testing Variables	Dependent Variables	Testing Method
[51]	2020	-	-	-	2–10	8	Fibre's content	Mechanical properties	Modulus of rupture, modulus of elasticity (MOE)
								Durability properties	Water absorption, fungal decay and termite damage
[52]	2015	-	Mix (20 + 50)	-	1–5	1	Effect of fibre content	Fresh properties	Slump and compaction factor
								Mechanical properties	Compressive and flexural strength, direct shear and rebound hammer
[53]	2021	-	-	-	0.1–0.3	-	Fibres type and content	Fresh properties	Flowability
								Mechanical properties	Compressive and tensile strength
								Thermal properties	Thermal conductivity
[54]	2021	-	-	-	0.5–2	0.5	Metakaolin ratio and kenaf content	Mechanical properties	Compressive, tensile and flexural strength
[55]	2021	-	5 and 400 µm	-	0.3–0.6	-	Effect of fibres size and content	Fresh properties	Flowability, setting time and heat of hydration
								Mechanical properties	Compressive strength
								Microstructural properties	SEM EDS mercury intrusion porosimetry
[56]	2021	-	30	-	1 and 2	1	Effect of sodium hydroxide and fibre content	Mechanical properties	Compressive and flexural strength
[57]	2020	75	Mix of (60–80)	-	0.25–1	1	Fibre type and content	Mechanical properties	Compressive, tensile and flexural strength
[58]	2020	-	Mix of (5 –15)	-	0.5–2.5	0.5	Fibre type and content	Mechanical properties	Compressive and flexural strength
								Thermal properties	Thermal conductivity
								Microstructural properties	SEM
[59]	2020	-	Mix of (5–15)	-	1–2	1	The influence of the strength grade and fibre content	Mechanical properties	Compressive strength, flexural strength, deformation behavior and toughness
								Microstructural properties	SEM and XRD

Table 4. *Cont.*

Ref.	Year	Fibre Diameter µm	Fibre Length mm	Optimum Length	Fibre Volume %	Optimum Volume	Testing Variables	Dependent Variables	Testing Method
[60]	2020	65.4	25 and 50	50	0–2	0.5	Effect of fibre length and content	Fresh properties	Slump, compaction factor and VeBe test
								Mechanical properties	Compressive strength, tensile strength, flexural strength and flexural creep
								Microstructural properties	SEM
[61]	2019	-	20	-	2.5	-	Barchip fibre/kenaf fibre ratio	Mechanical properties	Compressive and flexural strength
[62]	2019	-	50	-	0.75	-	The interfacial bonding behaviour between KFCC and cement	Mechanical properties	Shear test, compressive strength and tensile strength
[63]	2018	-	25 and 50	50	0.5–1.5	0.5 and 0.75	Fibre content and binder material	Mechanical properties	Compressive, tensile and flexural strength
[64]	2017	-	50	-	0.4–0.5	0.45	Effect of fibre content	Mechanical properties	Compressive, tensile and flexural strength
								Durability properties	Water absorption
[65]	2016	-	40	-	0–1.5	1	Curing conditions, fibre types and content	Fresh properties	Slump
								Mechanical properties	Compressive and flexural strength
[66]	2015	-	19	-	0.25 and 0.4	0.4	Fibres type and content	Fresh properties	Slump
								Mechanical properties	Compressive and flexural strength
								Durability properties	Water absorption and drying shrinkage
								Microstructural properties	SEM

The fibres' volume fractions can range from 0.25 to 2 vol.% in concrete [50]. While for KFRCC, Table 4 shows that the dosage is from 0.1 to 2.5 vol.%. However, few researchers have investigated the impact of KF content above 2.5 vol.%. The length of kenaf fibres used in most of the studies ranged from 10 mm to 80 mm. Both fibre content and length are expected to influence the mechanical properties of the KFRCC, as described later in this study.

3.1. Fresh Properties

Some researchers have demonstrated that natural fibres have a negative impact on the hydration of cement-based composites [1]. Gwon et al. [55] examined the effect of KF size and content on the hydration characteristics of cementitious composites. KF were employed in two sizes, with average lengths of 5 mm and 400 µm, respectively. The content of fibres ranged from 0.3–0.6%. The findings revealed that regardless of the size of the fibres, increasing the fibre content led to more delay in setting time. This occurrence can be attributed to the alkaline hydrolysis of lignin and the partial solubilization of hemicellulose in the fibres.

Rahman et al. [65] studied the effect of two different fibre types: kenaf fibres and horsehair fibre, with fibre volume fractions of 0.5% to 1.5%. The findings revealed that KFRCC exhibited lower workability compared to the cementitious composites containing horsehair fibre with the same content. This is because kenaf fibres absorb more water than horsehair fibre. As a result, the amount of water in the mix will be reduced, resulting in decreased workability. The percentage of water absorption for KF and horsehair fibres was determined to be 74% and 63%, respectively.

Figure 8 presents the slump height of different KFRCC mixtures [35–37]. The addition of fibre significantly decreased the slump of the unreinforced mixture. The degree of loss of workability increased with the volume fraction of the fibres. This reduction is due to the water absorption property of the hydrophilic surface of KF that makes the mixture stiffer and drier when additional fibres are used. Besides, the long fibres (50 mm) reduced the workability more than the short ones (25 mm). Because long fibres hold the mixture up and make it more flow resistant. This may also be attributed to the orientation and contact surface area of KF with the composite.

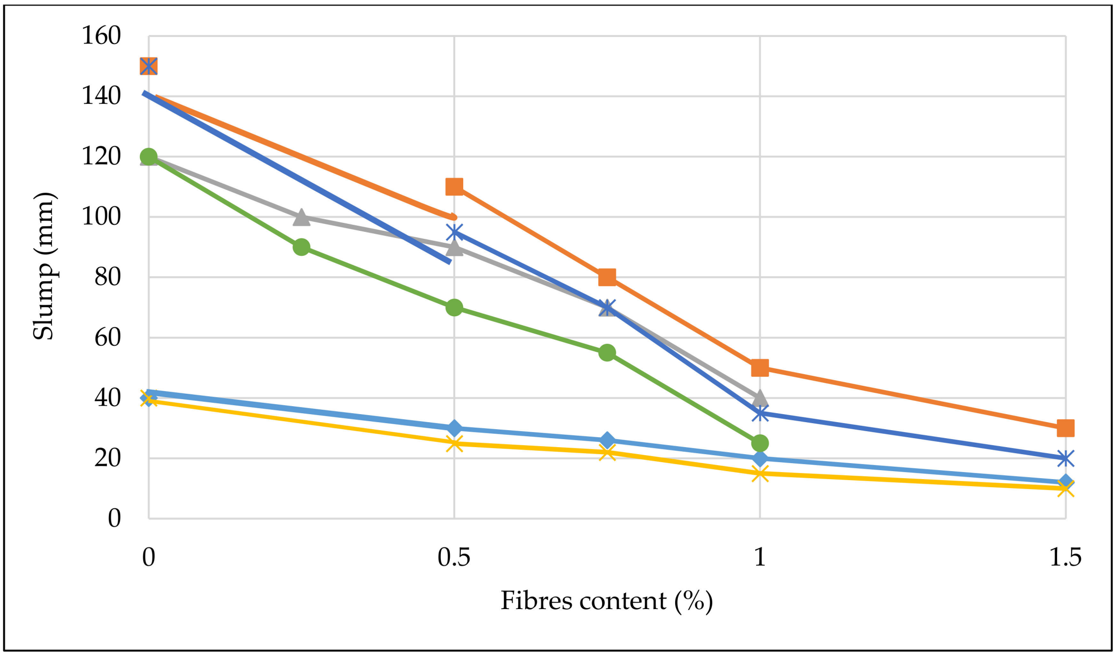

Figure 8. Influence of KF lengths and content on the workability of cement- based composites, data collected from the publications [35–37].

The use of steel fibres, basalt fibres, polypropylene fibres, and other types of natural fibres such as hemp, jute and coir fibres have also been found to reduce the workability of cementitious mixes [67–70]. In comparison to other fibres like polypropylene fibres, the research by Beddu et al. [53] showed that using KF in cementitious mixes produced better workability than using polypropylene fibres at the same volume fraction. The workability of the mixture containing 0.1% of polypropylene fibres was 34% lower than the control mixture without fibres. On the other hand, the workability of KFRCC containing 0.1% of KF was 29% lower than the control mixture.

Fibre pre-treatment alleviated the reduction in workability of mixtures by minimizing the water-absorbing chemical components of KF. The fibres may also be pre-wetted before use in mixtures to decrease the degree of loss in workability.

3.2. Mechanical and Microstructural Properties

The performance of cementitious materials is often measured in terms of their mechanical properties, like compression properties, flexural properties, tensile properties, and impact properties. Such characteristics are important for determining the material's capability, particularly under critical and severe conditions that are directly related to engineering performance [71]. In the last few years, several studies on cementitious composites reinforced by KF have been carried to describe their mechanical performance. The compressive, flexural and tensile strengths of KFRCC vary according to the category of fibres, their orientation (random or unidirectional), fibre type (fibres or fabric), treatment method, fibre length and fibre content.

Abirami et al. [57] incorporated 0.25–1% of different types of natural fibres (kenaf or sisal fibres) into the cement-based composite. The findings showed that the addition of both fibres increased the compressive and tensile strength by about 6.5% and 12.7%, respectively. The composites reinforced with 1% of sisal or kenaf fibres achieved the highest mechanical properties compared to the composites with other fibre dosages. Moreover, KFRCC achieved higher compressive strength and slightly lower flexural and tensile strength than the composites reinforced with sisal fibres.

Beddu et al. [53] studied the performance of cementitious composites containing 0.1–0.3% of KF or polypropylene fibres. The findings showed that KFRCC samples have higher compressive strength than the composites containing polypropylene fibres. However, the tensile strength improvements were higher in the cementitious composites reinforced with polypropylene fibres.

Guo et al. [9] examined the effect of the treatment method on the properties of single fibres and the performance of KFRCC. They used 0.25–0.75% of three types of KF; untreated (RKF), alkaline treated (AKF) and alkaline-hydrogen peroxide treated (AHPKF). The findings revealed that both treatment methods decreased the fibres' amorphous components and diameter and increased the tensile strength and surface roughness of the fibres. Figure 9 shows that the KFRCC achieved lower compressive and flexural strength than the plain matrix. However, the KFRCC containing treated fibres exhibited better performance compared to untreated fibres. This is an attribute of the lower content of amorphous components and better adhesion between the treated fibres and cement paste. Although there is no substantial difference in strength between KFRCC containing alkaline treated fibres and that containing alkaline-hydrogen peroxide treated fibres, alkali-treated fibres composites appear to perform slightly better than alkaline-hydrogen peroxide treated kenaf fibres in most cases.

Baarimah et al. [56] examined the effect of sodium hydroxide (NaOH) solution on the mechanical properties of KFRCC. They used the alkaline solution with three different concentrations (1%, 3% and 6%) and two different volume fractions of KF (1% and 2%). They observed that the KFRCC containing 1% KF treated with a 6% concentration of NaOH solution achieved the highest compressive and flexural strengths, as shown in Figure 10. This could be attributed to the reduction in the hydrophobic characteristic of the fibres that causes a delay in the internal hardening of KFRCC due to high water absorption.

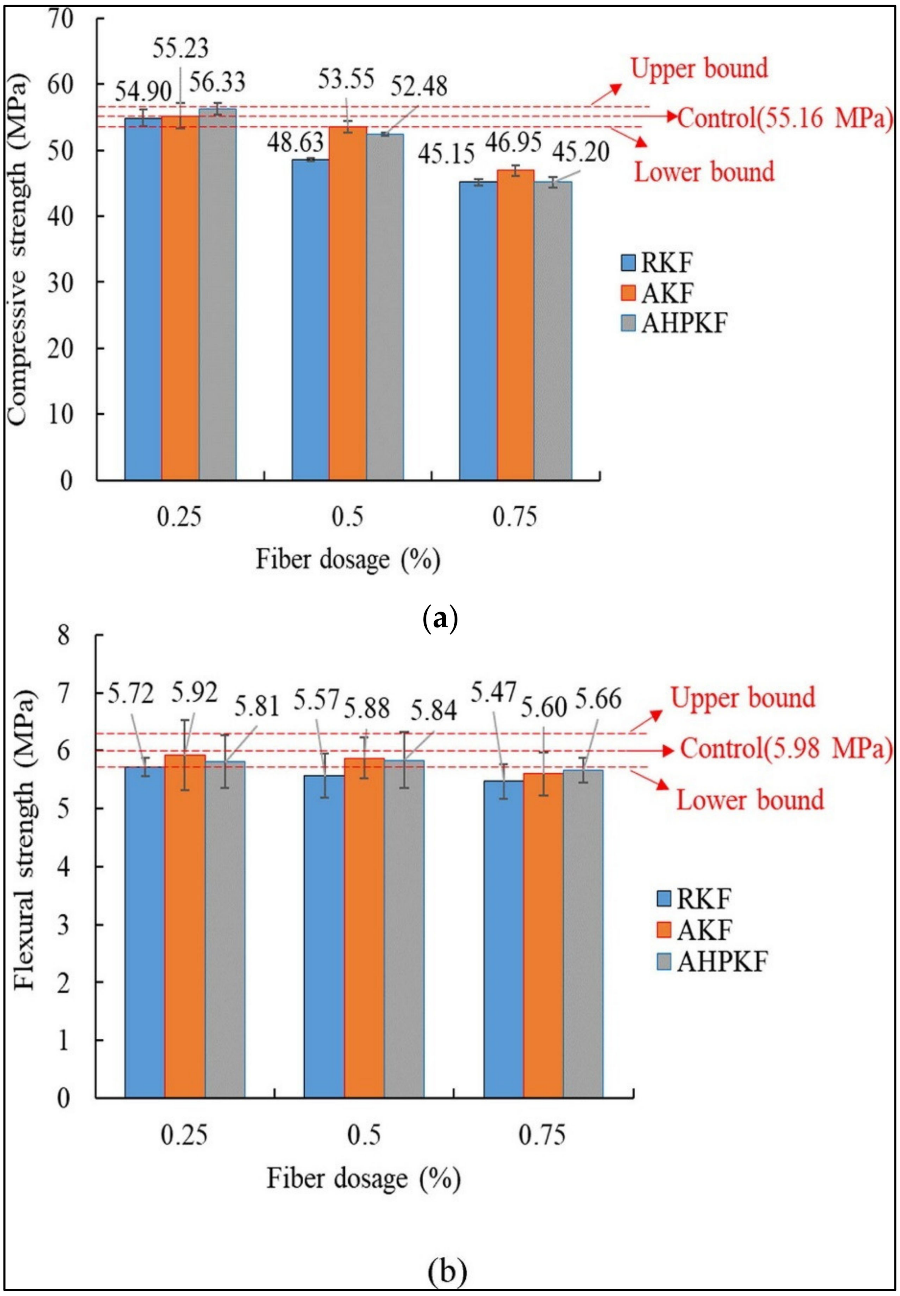

Figure 9. Impact of alkaline treatment method and fibre dosage on mechanical properties of KFRCC: (**a**) compressive strength and (**b**) flexural strength. Reprinted from [9] with permission from Elsevier.

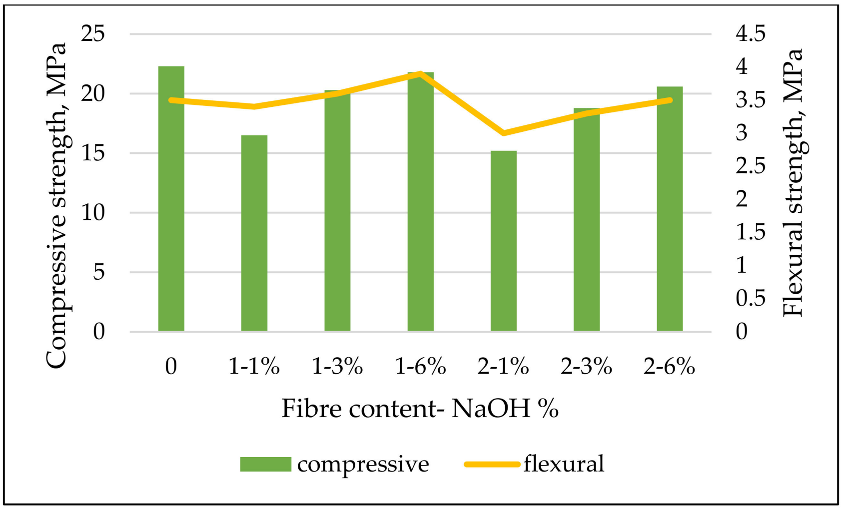

Figure 10. The effect of the sodium hydroxide (NaOH) solution and fibres content on the mechanical properties of KFRCC (data from [56]).

Azzmi & Yatim [36] made a comparison between the influence of KF with short length (25 mm) and long length (50 mm) on the compressive, tensile and flexural strengths of KFRCC. They observed that increasing the fibre content decreased the compressive strength for both fibre lengths. However, for the flexural and tensile strengths, there was an improvement of about 25.86% and 6.12% with the long fibres and an improvement of 26.07% and 25.8%, respectively, with the short fibres, compared to the plain matrix. There was an optimum fibre content of approximately 0.5% with using the long fibres and 0.75% with the short fibres. On the contrary, Lam & Yatim [35] and Babatunde et al. [37] reported that using KFRCC with 50 mm length achieved better performance in terms of strength properties, compared to 25 mm KF. The main reason for this contrast can be the water content. In the study by Azzmi & Yatim [36], they used a lower (W/C) of 0.53. So, adding KF with higher content and longer length made the mixture drier and resulted in difficulties in the placement, vibration and compaction of the mixture, thus reducing the strength. The strength reduction could be overcome by using the appropriate amount of superplasticizer, which can enhance the workability of the fresh mixtures, thus improving the mechanical strength of KFRCC [9].

Elsaid et al. [17] investigated the influence of KF's content on the mechanical properties of cement-based composites. The volume fractions of KF were 1.2% and 2.4%. The results showed that the addition of KF at any dosage reduced the compressive strength. However, the compressive stress-strain curve (Figure 11) indicated that although there was lower compressive strength, the KFRCC samples showed higher toughness than the non-fibrous matrix, and the value of strain at peak stress was within the range of 0.004–0.005, which is higher than the typical strain value of 0.002 for standard concrete. However, the strain is lower than the typical strain of 0.01 for mortar. This is attributed to the smaller diameter and amount of coarse aggregate utilized in the mixes when compared to normal concrete. KFRCC samples showed well distributed cracking patterns, higher energy absorption and exhibited more ductile behaviour.

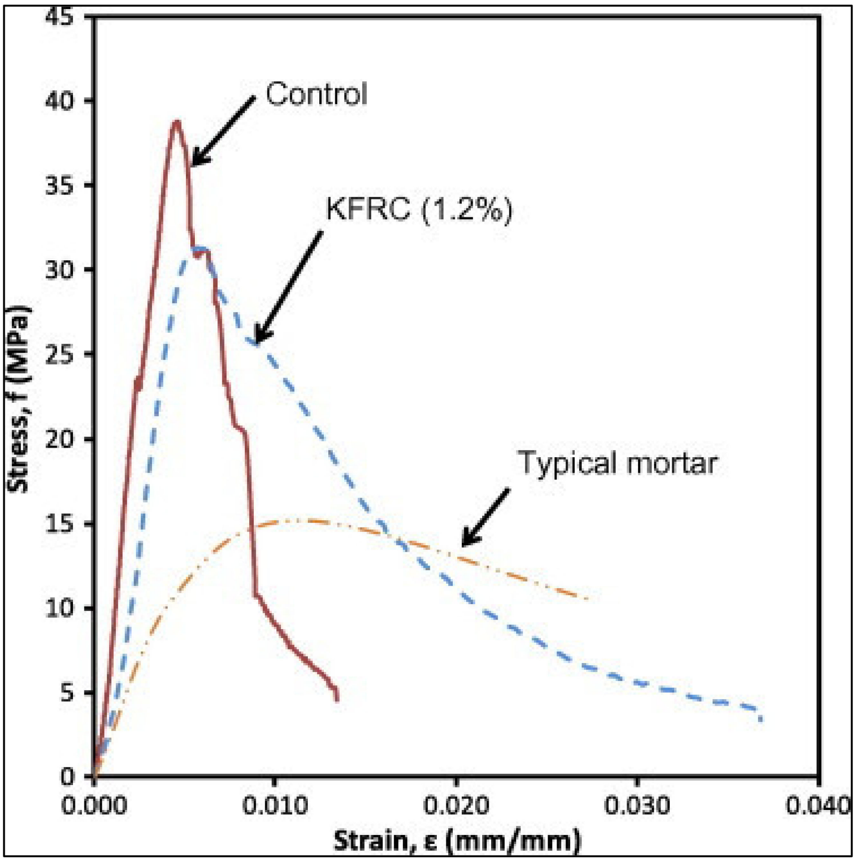

Figure 11. Stress-strain curve of the non-fibrous matrix (control) and KFRCC. Reprinted from [17] with permission from Elsevier.

Pirmohammad et al. [13] observed that the fracture toughness increases linearly with fibre content up to 0.3%. This increment is due to the high tensile strength of KF, which increases KFRCC resistance against cracks growth. Zhou et al. [59] reported that KFRCC demonstrated higher ductility by exhibiting less spalling and a slower formation of cracks under compression and flexure loads than the plain composite. As shown in Figure 13, there was a considerable amount of cement matrix and aggregates spalling in the plain sample. On the other hand, the KFRCC specimens had less obvious spalling on the surface. Kenaf fibres can act as bridges across microcracks induced by stress, preventing them from propagating in cementitious composites. Depending on their characteristics and amount, KF hold some of the load in the matrix and transfer the other to the uncracked parts of the specimen, resulting in multiple cracking [64].

The scanning electron microscope (SEM) images revealed good adhesion between the KF and the cement matrix [17,59,61,67]. Moreover, the pre-treated KF exhibited better adhesion with the cement matrix than the untreated fibres. The bonding of fibres to the cement matrix is a critical factor in determining the performance of the reinforced composites. This bonding behaviour leads to a considerable increase in the pull-out load properties [9].

An overview of the mechanical properties of KFRCC is shown in Figure 12 [17,37,58,60,62,65,66]. A reduction of about 10–53% in the compressive strength can be observed with the incorporation of KF. The reduction value increases with increasing the content and length of the fibres. Due to the fibre's agglomerations and decreased workability that led to entrapped air. However, the reduced compressive strength could be acceptable in most cases if it is still suitable for the proposed application and if other characteristics such as flexural and tensile strengths, as well as shrinking resistance, are improved. Similar strength reduction has been reported by using different types of fibre such as basalt [72], polypropylene [73], and coconut fibres [74].

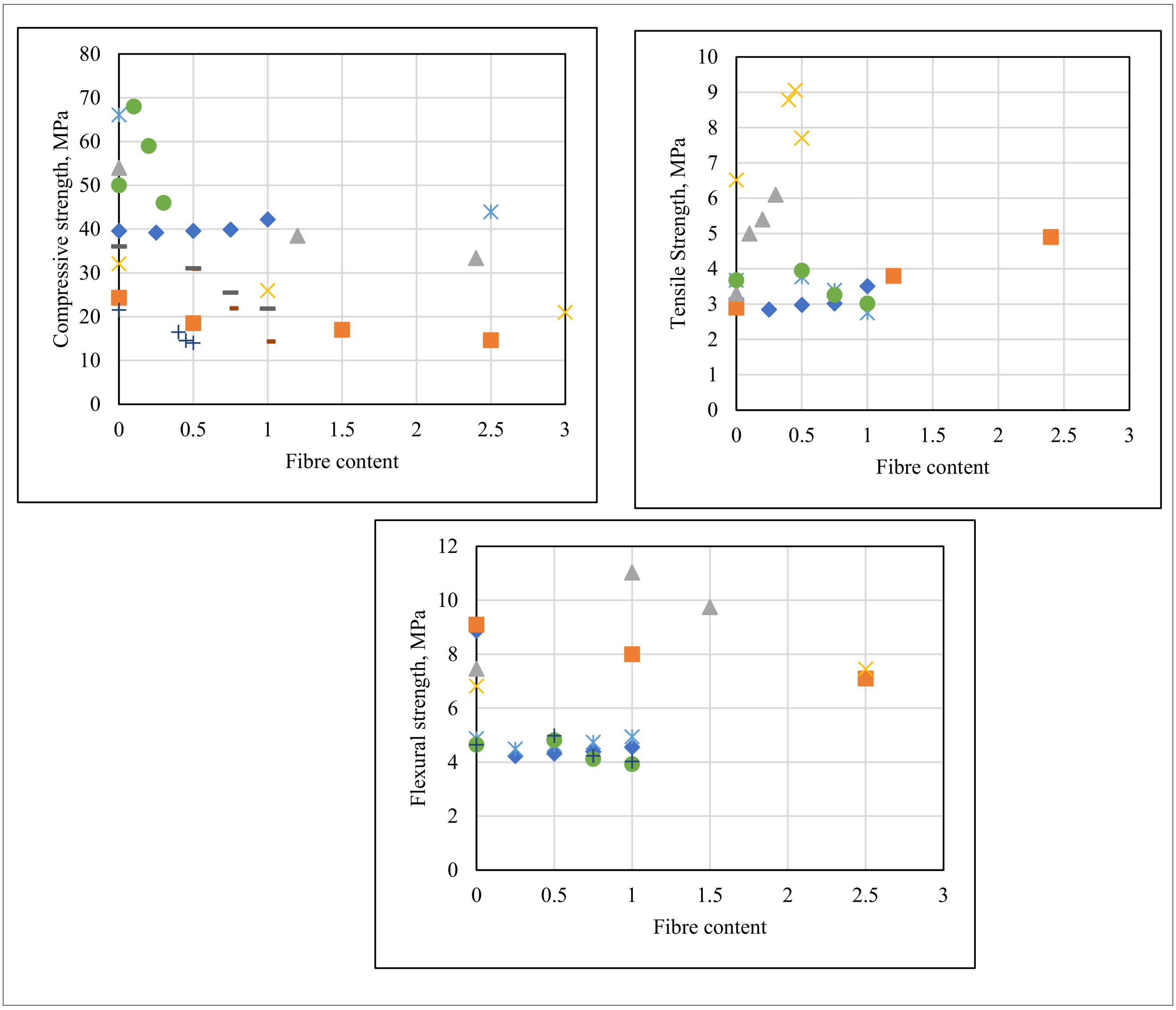

Figure 12. Influence of KF content on the mechanical strength of cementitious composites, data collected from the publications [17,37,58,60,62,65,66].

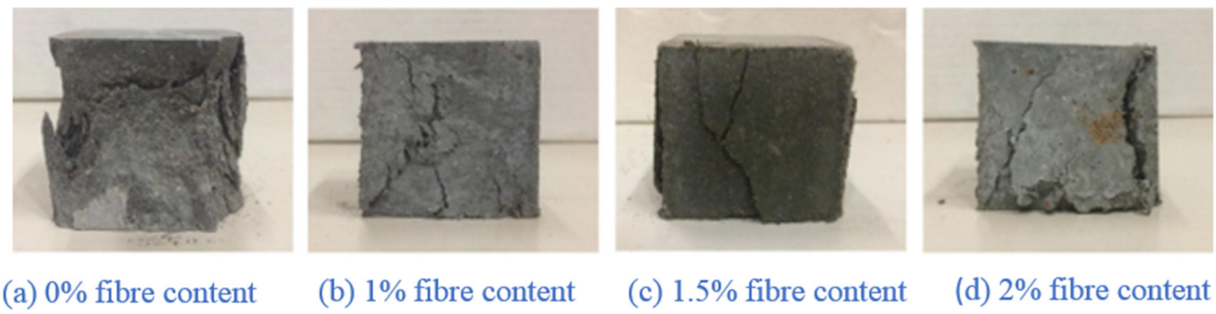

Figure 13. Failure patterns of cement composites. Reprinted from [59] with permission from Elsevier.

Also, Figure 12 demonstrates that the addition of KF into the cement-based composite improves the tensile and flexural strengths up to 40.8% and 32.3%, respectively, compared to the plain composites by using the appropriate content and length of the fibre. But, increasing the length and content of the fibres beyond the optimum value also causes a reduction in strength due to the fibre "balling", which occurs when fibres clump together during the mixing phase and causes difficulties with consolidation and non-uniform distribution. The strengthening effect of fibres decreases by non-uniform fibre dispersion. The enhancement in the tensile and flexural strengths of the composite will be lost if the fibres are inadequately distributed and oriented perpendicularly to the load direction. Thus, before utilizing KF on a large scale, it is recommended to conduct a preliminary study to determine the optimal length and content of KF for a specific application of cementitious composites.

3.3. Durability Properties

While a significant number of studies were carried out on KFRCC's mechanical properties, considerably fewer studies on its durability properties are reported, as shown in Table 4. For effective application in construction, long-term durability performance also needs to be achieved along with mechanical performance.

The change in the volume and/or length of concrete samples due to shrinkage results in a large number of cracks, which is a big concern for all engineers and designers. Babatunde et al. [37] observed that the drying shrinkage of concrete significantly reduced with adding 0.5% of KF. This reduction is due to the ability of KF to hold moisture. Also, the randomly oriented fibre presence around the cement mortar creates a confining environment that prevents the progression of drying shrinkage in the samples. Internal cracks may form as a result of shrinkage, which will cause tensile stress. The internal fibres in the cement-based composite cannot only resist the tensile stress but can also lower stress concentration at the tip of the crack, preventing the crack from developing further and small cracks from joining together and becoming larger cracks.

Similarly, in a recent study, Guo et al. [75] assessed the influence of KF on the durability performance of cementitious composites. The fibre volume fractions were 0.25% and 0.50%. The results showed that the inclusion of KF not only decrease the autogenous shrinkage potential but also substantially decrease the cracks of the drying shrinkage. The samples reinforced with 0.5% KF showed better performance than samples containing 0.25% KF because, with increased fibre content, KF can absorb more water for internal curing, which provides higher resistance to shrinkage. Besides, the reduction in drying shrinkage cracks is mainly because more fibres provide more channels of bleeding to replenish the drying surface, forming more bridges to connect cracks and prevent their propagation. As can be seen in Figure 14a, the single cracks connect together and then develop into major cracks in the plain composite. However, KF can act as bridges and prevent the development of cracks in the KFRCC (Figure 14b,c).

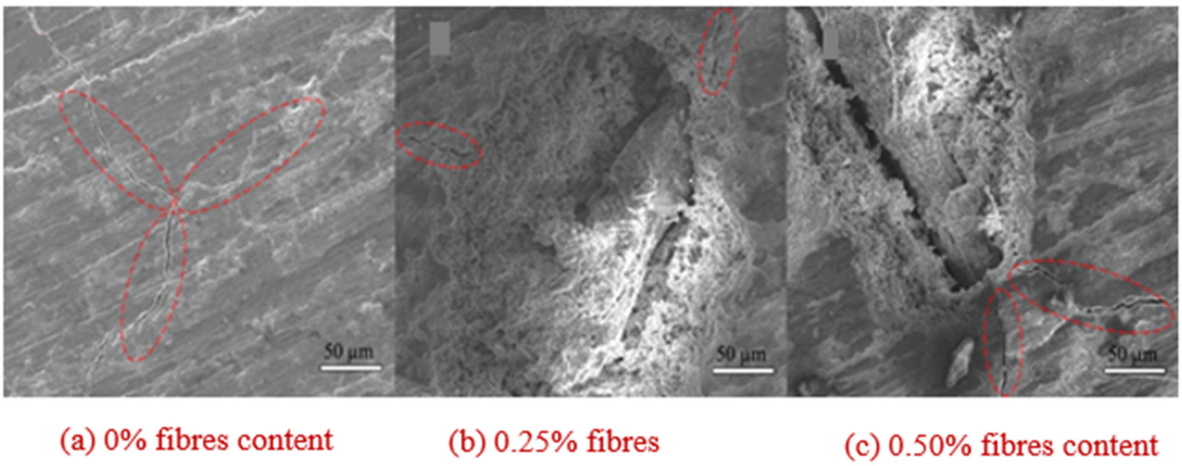

Figure 14. SEM images of cracks of the drying shrinkage. Reprinted from [75] with permission from Elsevier.

Sivakumaresa & Rymond [76] studied the durability of the cementitious composites containing different types of fibres: kenaf, coir and polypropylene fibres exposed to sulphate (Na_2SO_4), acid (HCl) and chloride (NaCl) attacks. The findings showed that regardless of the immersion media, all cementitious composites reinforced by fibres lost considerable weight and compressive strength. The KFRCC experienced the highest weight loss percentage and compressive strength loss. Due to the higher absorption capacity of KF, it can absorb more solution, which results in more deterioration of the KFRCC.

Sadia et al. [21] conducted research to evaluate the effect of the alkaline treatment on the durability properties of the cementitious materials by utilizing two different types of KF: treated and untreated KF. The results showed that the KFRCC containing treated fibres exhibited the least water absorption, lowest initial surface absorption, and least drying shrinkage deformation compared to the KFRCC of untreated KF or the plain cementitious matrix. It was because treated fibres act as a neutral blockade that hinders the water permeation into the capillary pores. The treatment increased the roughness of KF, thus improving the fibre-matrix adhesion, which enhanced the performance of KFRCC reinforced by treated fibres [21]. However, the mechanical characteristics of treated composite showed adverse shortcomings when subjected to wet/dry cycling, resulting in a lower compressive strength compared to KFRCC containing untreated fibre. The alkaline treatment decreases thermal protection from direct heat, resulting in decreased ductility. As a result, after the initial breaking plane, fracture of the brittle treated fibres occurs immediately, leading fibres to fracture rather than pull-out.

Arunachalam & Jayakumar [66] examined the water absorption and drying shrinkage of cementitious composites reinforced by KF and polypropylene fibre. The results showed that both reinforced composites exhibited superior properties compared to the plain matrix. Both kenaf and polypropylene produced positive results, and there was not much difference in water absorption and shrinkage performance between these two composites.

4. Discussion

The applications of kenaf fibres in cementitious composites are increasing due to the number of advantages they provide over synthetic fibres. However, the surface treatment of KF is essential before their embedment in composites to eliminate the limitations of natural fibre composites such as low wettability, weak fibre-matrix interfacial adhesion and water absorption. The alkaline treatment is one of the most widely used methods to modify KF surfaces due to its effectiveness and low cost. It is clear from the current literature that the treatment method had a huge effect on the fibres and the composite's properties. However, only a few modification methods have been used in the KFRCC studies. Therefore, conducting studies on the impact of the various modification methods on the properties of KFRCC is highly recommended.

The inclusion of KF decreased the workability and delayed the setting time of cement mixtures. As shown in Figure 8, the general trend was, decrease in workability with increased KF length and content. However, pre-treating the fibres before being included in cementitious mixtures can overcome these limitations. Moreover, the use of chemical admixtures may also enhance the performance of KFRCC in the fresh state.

Most of the previous researches have shown that the KFRCC has lower compressive strength than the plain cement matrix. The reduction in the compressive strength was also reported when other types of fibres like the coir, sisal, and polypropylene fibres were added to the cementitious mixtures. This is in line with the general understanding that the primary function of fibres is to control the propagation of the cracks in composites rather than increase compressive strength. The reduction in the compressive strength can be overcome by using supplementary cementitious materials such as fly ash. The fine fly ash particles' ball bearing impact can provide a lubricating effect. It reduces the water demand and improves workability.

On the other hand, the inclusion of KF in cementitious composites increased the tensile and flexural strengths up to 40.8% and 32.3%, respectively, compared to the plain composites. KF control the micro-cracks propagation, resulting in enhanced ductility, crack pattern and fracture energy of the cementitious composites. However, before using KF on large scale applications, it is essential to determine their optimal content and length. Due to the limited range of findings, it is difficult to determine the optimum length and volume fraction of KF. However, a 0.5–1% fibre ratio may be sufficient to achieve a workable mix with a suitable strength improvement.

In terms of durability performance, the addition of KF, which is an inexpensive and biodegradable material, can effectively enhance the shrinkage performance of composites. However, further research is needed to thoroughly understand their effect on long-term performance.

This review is expected to be a good reference to scientists, engineers and other people interested in using this environmentally friendly material to improve the performance of cement-based composites. More studies and development on the application and understanding of KFRCC is also hoped to result from this work.

5. Conclusions and Future Outlook

- KF are cost effective and environmentally friendly alternative to traditional fibres that can be utilized to improve the mechanical properties and durability of cementitious composites.
- KFRCC mixtures have lower workability and longer setting time than plain cementitious mixtures. Fibre pre-treatment can alleviate the reduction in workability by minimizing the water-absorbing chemical components of KF.
- The incorporation of KF in cement based-composites reduces their compressive strength. This is in line with the general understanding that the primary function of fibres is to control the propagation of the cracks in composites by bridging across cracks and providing post-cracking ductility rather than increasing compressive strength.
- The use of the appropriate length and content of KF improves the tensile and flexural strengths of cementitious composite. KF control the micro-cracks propagation, resulting in enhanced ductility, crack pattern and fracture energy of the cementitious composites.
- KF can effectively enhance the shrinkage performance of cement-based composites. However, further research is needed to thoroughly understand their effect on long-term performance.

The findings and observations in this review indicate that KFRCC can be used in the construction of road pavements, slabs and other similar applications with reasonable engineering properties under sustained bending loads. Also, KFRCC is lightweight and ideal for use in roofing, ceiling, and walling for the construction of low-cost houses. On the other hand, future research studies on the large-scale application of KFRCC, as well as its performance in fibrous concrete structural components are needed. Future studies should focus on the use of cementitious inorganic admixtures to compensate for the volume of cement used in the manufacture of KFRCC, as well as a comprehensive life-cycle assessment of the KFRCC. More research is needed on the properties discussed, as well as new investigations on the effects of KF on the other properties of cementitious composites, including carbonation resistance, the resistance of abrasion, thermal resistance and conductivity. Also, further studies are required to explore the influence of KF pre-treatment techniques on the performance of cementitious composites since these techniques appear to have a huge impact on the properties of the fibre and the matrix. An approach of employing the water retention capacity of KF to develop high-performance cementitious composites through internal curing technologies should also be investigated.

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