A review of the mechanical and durability performance of kraft-fibre reinforced mortar and concrete

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Abstract

The building and construction industry is one of the leading generators of waste in the worldwide economy. Use of excessive quantities of virgin materials to manufacture building materials is a growing dilemma that needs urgent attention. With the excessive general of waste, research focus has been directed toward the use of waste to substitute and reduce the requirement for immense extraction of virgin materials. After glass and plastic, cardboard is considered as the most prominent recycled waste material that could possess potential use in mortar and concrete applications, thereby reducing virgin material extraction. The current study aims to conduct a systematic review in using cardboard waste in mortar and concrete. A bibliometric assessment of 874 research publications demonstrated that cardboard waste related studies on mortar and concrete remain seldom considered. An analysis of literature indicated kraft fibres within cardboard can be recycled into building materials. The key findings discovered matrix modification and fibre pre-treatment are essential for the enhancement of mechanical and durability properties. Researchers have developed mix designs including supplementary cementitious materials (SCM) to mitigate fibre degradation and enhance mechanical values. However, further research is required to comprehensively analyse an effective material matrix to reduce the degradation caused on the fibre. Therefore, this paper presents key findings of current trends, limitations and future research directions related to the use of recycled cardboard in concrete and cement-based materials.

Keywords: Cardboard waste; cement replacement; concrete composites; kraft fibres

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1.0 Introduction

Minimising the negative impacts of the construction industry on the environment has been a research focus for many decades. The construction industry is one of the largest sectors that contribute to waste generation in the world [1, 2]. Islam et al. [3] highlight that 30-40% of all waste created is due to construction and demolition (C&D) works, even more so in Australia (44%). During the construction phase, a vast proportion of materials used contains a percentage of waste, whereas demolition works can contain 89% waste from all derived materials [4, 5]. Various research studies have been conducted on the causative factors and preventive measures of waste generated [5]. These studies found that waste can be linked during all construction phases including; design, procurement, construction activities and lifecycle of the project. Many construction companies have adopted measures to reduce the materials required on site using methods and software such as the lean approach, prefabrication, BIM and CAD. However, these measures are not always suitable due to the fragmented nature of construction activities and the unique nature of each construction project. Although, in recent years BIM technology is becoming increasingly efficient, it is yet to be utilised effectively across the industry, especially in residential building construction.

Households are the third largest industry of waste generation, following construction and manufacturing [6]. The growth in population correlates to the consumption of natural resources as well as the generation of waste materials. Currently, the world generates around 2 billion tonnes of solid waste annually with the forecast of waste materials to increase by 70% globally by 2050. Solid waste treatment and disposal centres generated an estimated total of 1.6 billion tonnes of carbon dioxide (CO_2) equivalent greenhouse gas emissions in 2016. If no improvements are made, this figure is set to increase to 2.36 billion tonnes by 2050 [7]. More than 50% of waste generated from households will result in the addition of landfill [8]. However, countries like Sweden have banned the waste release to landfill, with 98% of the waste being reused or recycled. The waste materials are processed back into useable products or transferred into an incineration system to generate heating and electricity. One tonne of incinerated waste could generate one hour of power for 900 Australian households [9]. Although this system significantly reduces environmental issues of waste disposal, it does not reduce the extraction of virgin materials.

The building and construction industry consumes approximately 31% of all extracted natural resources worldwide [10, 11]. Therefore, a contemporary solution must be addressed to minimise the negative effects of waste and resource extraction. Researchers [11-13] have indicated to sustain a viable solution, there must be a direction toward a circular economy. The framework of a circular economy is a system that eliminates a material "end of life" by keeping the material or product "in flow" via effective re-use strategies and methods. This reduces the extraction of virgin materials as well as mitigating the negative effects of waste accumulation [12]. Redirecting waste into building construction products and materials could significantly address both the issues of waste diversion and reduce the extraction of virgin materials. This will have the potential to alleviate environmental issues across the major contributing sectors.

Local Governments are required to combat the increase of waste generation with more sustainable measures. Increasing the cost of waste deposited at local council and landfill sites has been effective in Hong Kong and however, as a result, other issues of illegal dumping increased [14]. Maximising the economic benefits with recycling has shown to minimise waste with materials, especially with materials such as steel and concrete [3, 4]. The motivation for improving the environmental impacts are often linked to financial incentives. This is further shown with an annual generation of 8.7 million tonnes of concrete aggregate stockpiled due to financial incentives from local Governments within Australia [15]. The issues of waste development can be drawn to the end-of-life application of the materials. Wu et al. [14] classified waste materials as inert and non-inert components. The list of common construction waste includes timber, metal, paper, cardboard, plastic, rubber, textile, fiberglass, nylon and domestic waste. Inert materials are more commonly reused in land reclamation and site formation works. Those materials include concrete, rubble and soil. However, non-inert materials that are not suitable for land reclamation often end its life cycle in landfill. Those materials include cardboard, fibreglass, nylon, plastic, rubber and textiles. After plastics, cardboard is the highest contributor to landfill [16] and with heavy previous research focus on the former waste type, reusing cardboard is gaining significant popularity in research fields [17]. Research of cardboard waste has remained relatively static due to the concept the material is completely recyclable. However, the progression of experimental research is indicating the fibres contained within cardboard (kraft fibres) can be further used in composite designs [18, 19]. This is shown with researchers using the material as a reinforcement agent or partial filler in both plastic and cement matrix composites.

2.0 Research significance and methodologies

Fibre composites have been a part of building and construction materials for several decades with synthetic materials at the forefront due to enhanced mechanical benefits [20-24]. Nowadays, there is a focus towards sustainability with natural fibres (NFs) becoming increasingly researched. The successful integration of NFs within cement-based composites can reduce the manufacturing of other non-natural fibres. There are several research review articles on NFs within composite materials [25, 26]. However, none have focused primarily on the integration of kraft fibre (KF). Although many research articles focused on kraft fibres/ pulp, the limitations and barriers have not been explicitly detailed. KFs and NFs have similar reactions when applied within a cement-based composite however, the removal of key amorphous components such as lignin and hemicellulose of NF cause the KFs to react differently when compared to virgin NF. Therefore, the outcome of this review will enable readers to identify current composite design research of KFs and understand the results of those designs via mechanical and durability analysis. This will further allow stakeholders to identify and understand the factors that affect the successful integration of KFs for further use within composite designs.

This research study will begin with a focus on waste fibres used within the building and construction industry and cement-based composite materials using a bibliometric assessment. A bibliometric assessment is a comprehensive science mapping analysis of research publications. The bibliometric assessment is conducted via a bibliography analysis software called "Bibliometrix". The software can highlight current trends of research as well as identifying knowledge gaps within published literature [27]. The search engine used for sourcing publications was Web of Science "WoS", using two main criteria points of "Waste fibre* in Building construction" and "Waste fibre* in cement and concrete".

The asterisk was included to broaden the search by finding words that start with the same letters. This is commonly adopted by researchers using the search engine WoS and can also be known as a "wildcard". The time period analysed ranges from 2000-2020. The results of the WoS search included journal articles, books, book chapters and conference publications which have researched waste fibre materials used in construction as well as cement and concrete applications. The output of the review is a systematic approach of current published literature as well as the inclusion of results and observations obtained from the bibliometric assessment, as illustrated in Figure 1. The review aims to highlight current waste fibres currently used in the building construction industry and conduct a thorough viability analysis of mechanical and durability properties of a waste material currently not being utilised.

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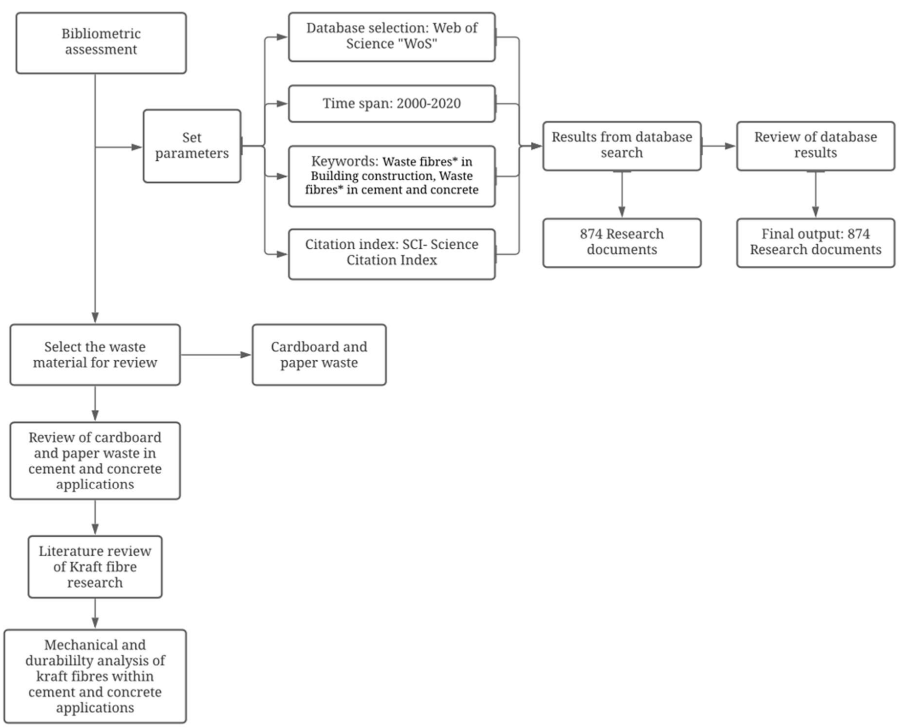

Figure 1 Research methodology

3.0 Bibliometric analysis findings

The main information derived from the bibliometric assessment is shown in Table 1. The assessment reviewed 874 documents from 362 journal and book sources. There were 2393 authors and 3232 author appearances. These values represent the numerical distribution between articles, book chapters, review and proceedings paper of the authors and co-authors. The average number of authors per document is

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represented at 2.74, with co-author ratio calculated via author appearance and documents. This value correlates with the collaboration index as represented at 2.83, indicating the mean number of authors in a multi authored article. These values represent a high collaboration on published research within the fields of waste fibres in building construction and waste fibres in cement and concrete materials.

Table 1 Main information derived from the bibliometric analysis

Description	**Results**
Period	2000- 2020
Documents	874
Sources (Journals, Books, etc.)	362
Keywords Plus (ID)	1258
Author's Keywords (DE)	2303
Average citations per documents	12.58
Authors	2393
Author Appearances	3232
Authors of single-authored documents	36
Authors of multi-authored documents	2357
Single-authored documents	42
Documents per Author	0.365
Authors per Document	2.74
Co-Authors per Documents	3.7
Collaboration Index	2.83
Document types	
Articles	620
Article Book Chapter	9
Article Early access	12
Proceedings paper	170
Article Proceeding Paper	11
Review	49
Review early access	3

Figure 2 illustrates the most frequently published journal sources with the number of documents published. Journal of Construction and Building Materials is the most prominent publication source with the highest publications since 2000. The Journal scope and high number of publications indicate a prominent research focus of experimental studies to improve the integration of waste fibre that can be used within building materials. However, with the focus of using natural materials within the building and construction industry, the number of publications in the Journal of Cleaner Production is subsequently rising.

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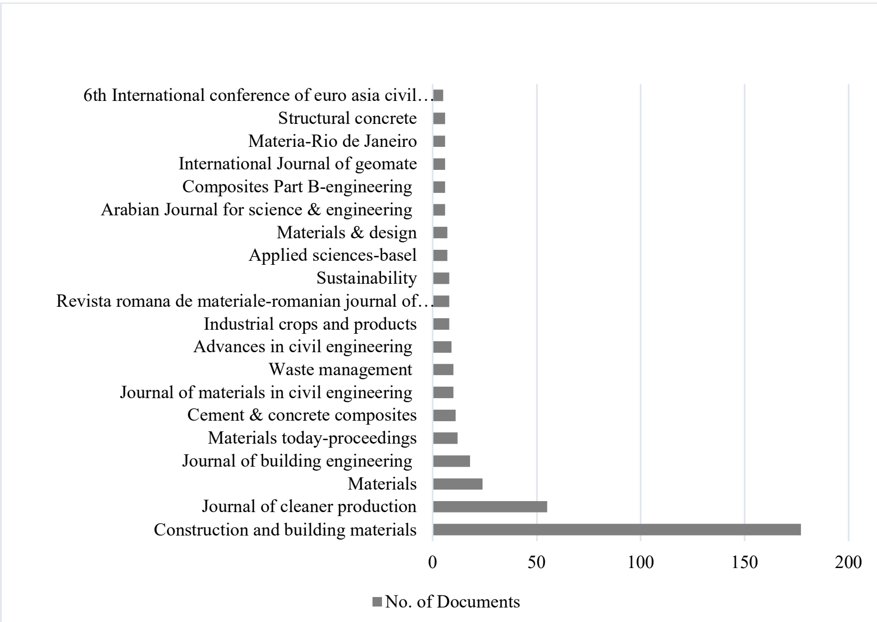

Figure 2 Publishing source vs number of publications

There is an exponential growth of publications in the last 3 years (2017-2020), as illustrated in Figure 3, which can be related to the further research focus toward sustainability of waste materials within the industry. Published articles were in single digits from the year 2000-2008, with a steady rise following 2009. This can be linked with an increased global awareness of climate change, with significant concerns over air pollution at the 2008 Summer Olympics held in Beijing [28]. In 2009, the Environmental Protection Agency of the United States announced that greenhouse gases endanger the health and welfare of American citizens by contributing to climate change [29]. Following the announcement, the next 8 years exemplified a steady increase in publications until 2017, where publications rose from 55-103, then followed with an exponential upward trend to 157-150 annual publications. The significant increase of research can be attributed to the 2030 Agenda for Sustainable Development set out by the United Nations [30]. The previous years' saw the development of the Paris Agreement on Climate Change which set out an urgency among nations around the world. With these global events, researchers identified gaps in literature and experimental studies rose with the aim of reducing greenhouse gas emissions at the forefront.

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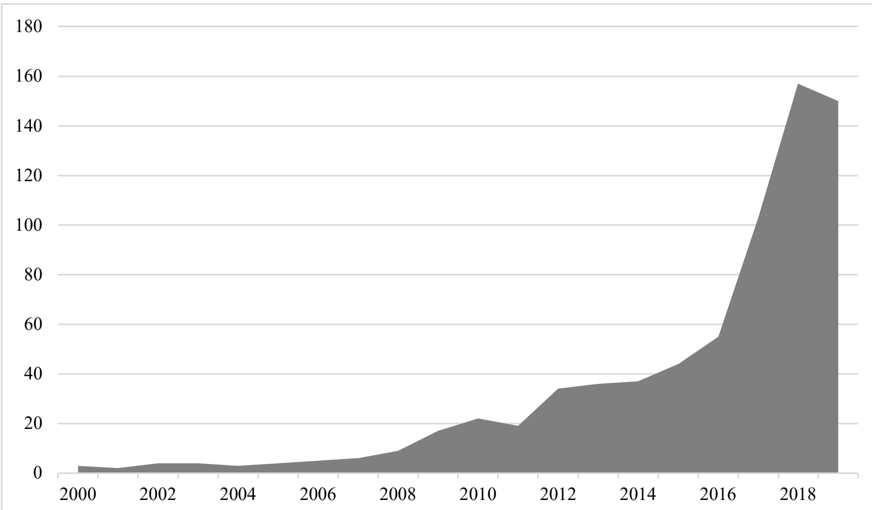

Figure 3 Annual scientific publications on waste fibres used in building construction materials

The thematic word map of the bibliometric assessment is shown in Figure 4. The data analysed common word occurrences throughout each publication, highlighting the variations of waste materials and other key research focus areas. Due to the search criteria containing cement and concrete, a significant amount of published research articles refers to the topics of mechanical properties and other material mechanics such as durability, workability, compressive and flexural strength. Although extensive research has been focused on the integration of Ground blast furnace slag (GBFS) in cement and concrete materials, the bibliometric assessment has focused primarily on the integration of fibres used with or without partial supplementary cementitious materials (SCM)s. As shown in Figure 4, Fly Ash (FA) has been the prominent experimental research focus of a partial cement replacement. Glass, plastic, steel, tyre and rubber waste are the other waste materials that are strongly researched areas in building construction materials. In recent years, these materials have mainly used as a filler material in roads and pavement sub layers [31-33]. NFs and cellulose were also mentioned however, only sisal fibres were specifically targeted as the NF used. KFs that are derived from NFs used in the manufacturing of cardboard was not mentioned in this assessment. With cardboard and paper waste significantly contributing to landfill worldwide [19], the bibliometric assessment has indicated a gap in literature for the further use of KFs derived from those waste materials.

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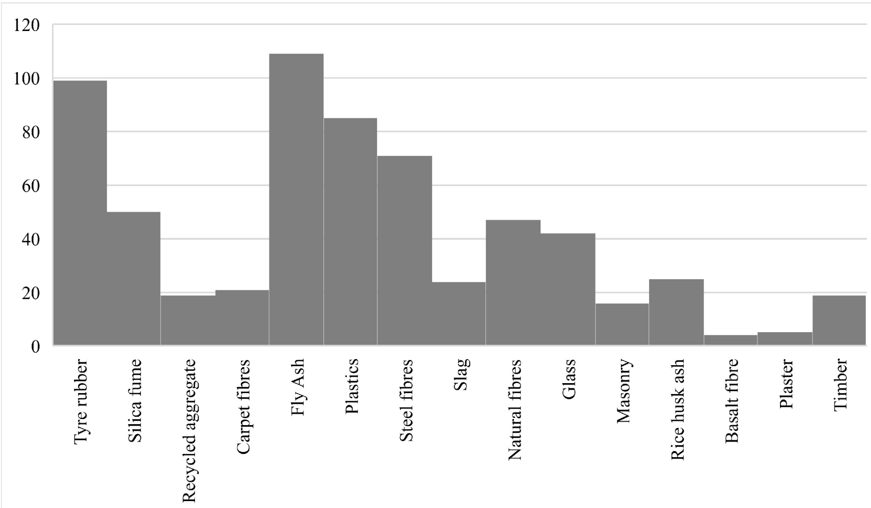

Figure 4 Thematic map of word occurrences

3.1 Summary of findings

The bibliometric assessment shows the following key observations and results.

- The results from the bibliometric assessment has shown a prominent research focus toward experimental designs with minimal research attention toward the sustainable and economic benefit of redirecting waste in construction materials.

- When waste materials are integrated as a partial cement replacement, the bibliometric assessment has shown that Fly ash has been heavy researched material when integrated in concrete materials. Other researched SCMs were Silica Fume and Ground blast furnace slag. However, the former waste materials were not as prominent.

- The primary publication source of waste fibres in building construction and waste fibres within cement and concrete materials is the Journal of Construction and Building materials. This is due to the Journals scope of innovation, focusing on investigative measures such as experimental material designs for building construction materials.

- Common non-inert waste materials such as textiles, cardboard, fibreglass and nylon were not listed within the word occurrences sourced from the 874 research publications.

- The results from the bibliometric assessment did not contain the term “kraft fibres”. This shows that significant research has not been conducted on the constituent fibres within cardboard waste material.

- The findings showed that significant research of plastics and tyre rubber have been associated with building construction materials. The waste materials were highlighted in literature as emerging trends of road and pavement sub layers.

The findings from the bibliometric assessment have allowed future researchers to identify influential journal sources and target waste research focus areas. Based on the findings, it was shown that the predominant materials researched were fly ash, tyre rubber and various plastics. Due to the array of listed waste materials, this review will therefore promote the viability of cardboard waste used further in building and construction materials. The bibliometric assessment has identified a gap in literature regarding the use of KFs derived from cardboard waste and therefore a comprehensive analysis is required to inform readers of current experimental trends and opportunities for future research.

4.0 Kraft fibres

In recent years, growing interest has been directed towards natural fibre composites (NFC) [34]. This has been primarily due to the improved sustainability and biodegradability aspects when replacing synthetic materials. However, the advancement of integrating NFs has been largely disrupted because of the reduced mechanical and durability properties when applied within a cement matrix [25]. NFs can include mineral and various plant species. Each fibre type contains specific material properties and can be used accordingly to the product requirements. Mineral fibres such as asbestos were used extensively as a reinforcement agent due to its ability to deflect the deterioration caused by a high alkaline environment. However, the material has significant health implications on human life [35]. Therefore, the focus on plant fibres has been of interest due to its non-hazardous nature and other significant advantages, as detailed further. A common extraction method to obtain NFs from plants is called kraft processing. This is completed with chemical additives or a thermomechanical process [18, 35]. This method is predominant in the paper and cardboard industry and is prevalent across the globe. After the completion of this processing system, the fibres are called kraft fibres (KF) or kraft pulp (KP). These fibres primarily contain cellulose matter and can be the main reinforcement element if used in building and construction material applications.

The integration of KF within cement-based composites has been challenging due to the severe fibre degradation caused by the high alkalinity of the environment [18, 36]. A successfully functioning composite material is only truly effective when the materials within the matrix are cohesive and thoroughly bonded. As the stress load transfers within the matrix, it must successfully alternate until it reaches the reinforcement agents within the composite [37]. An example is shown with steel reinforcement within concrete materials. A similar result is required of the fibres micro-mechanics within a composite application. Therefore, significant research has been undertaken to modify the matrix of the composite [38] to allow for the fibres to maintain their strength characteristics. Other research focus areas have involved fibre pre-treatment to mitigate the degradation caused [39]. However, currently composites with KFs are still negatively affected mechanically and a thorough review has not been explicitly examined. In order to attract a significant industry valorisation, the integration of KFs within cement and concrete materials pose a suitable opportunity. This is primarily because of the enormous volume of KFs produced worldwide annually [40]. The present work shows the progress and engineering issues when KFs are used in cement-based composites.

The advantages and disadvantages of KFs are like that of NFs and are highlighted further in Table 2. However, components of NF are removed during the kraft process, this is further explained below. KFs can withhold high tensile strength, improve flexural toughness of composites, enhance crack resistance and reduce fatigue behaviour [41]. However, the ability for the fibres to perform at a high standard is dependent on the environment at which it is applied. Within a cement-based matrix, KFs can deteriorate due to the high alkaline-mineral properties of Original Portland Cement (OPC) [42]. Therefore, the deterioration of KFs must be mitigated to ensure the mechanical and durability properties of the composite are maintained. This is especially critical for the promotion of these fibres to be integrated within cement and concrete composites for a widespread commercial application. It is important to note that a key difference between KFs and NFs is the ability of NFs to withhold moisture in the fibre cell walls. Jongvisuttisun and Kurtis [43] have found that this factor can aid in the mitigation of autogenous shrinkage within the cement paste during the hydration phases. However, as illustrated in Figure 5, excessive moisture within the fibre cell walls of NFs can lead to premature crack inceptions of the composite microstructure upon evaporation.

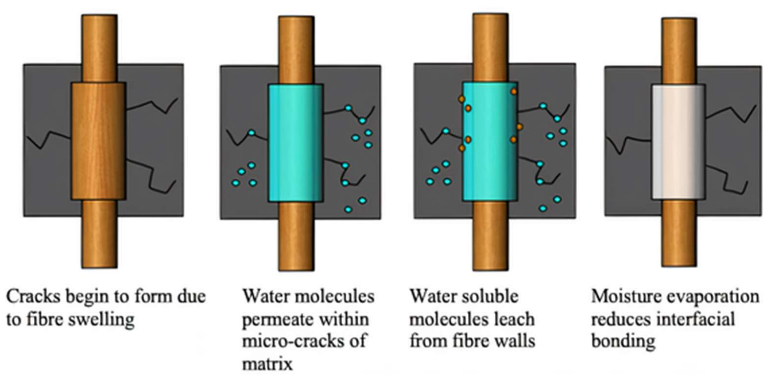

Figure 5 Consequence of NFs containing moisture within composite matrix. Redrawn from [44]

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Table 2 Advantages and disadvantages of Kraft fibres

Advantages	Disadvantages
Low density and high strength	Lesser durability compared to synthetic materials
Minimal reprocessing	High moisture absorption
Alternative waste sources of KF	Low modulus of elasticity
Non-abrasive material	Higher variability of fibres
Non-hazardous nature	Lower processing temperatures
Biodegradability	Dimensional instability

KFs have been applied to various composite designs to enhance the reinforcement properties as well as a partial cement replacement. However, as discussed, the successful application of KFs is dependent on several composite factors. The main factors that affect the successful integration of KFs within cement-based composites are the material selection within the matrix, fibre percentage and dispersion. When those factors are successfully determined, there should be minimal fibre degradation with a maximum interfacial strength between the fibre and the matrix [18, 25]. These factors are all dependent on the final material selected and must be thoroughly examined prior to a mix design phase. The environmental benefits of using NFs have been at the forefront of research focus. This is shown with efforts of minimised cement consumption and reduced energy requirements of other synthetic fibre materials. However, researchers have shown a variety of positive effects when KFs are integrated within composite designs. The benefits are an enhancement of mechanical properties including a reduced crack width when under implied loads. Minimised composite thickness and a reduction of weight in tall structures. There is also a resistance to plastic shrinkage during the hydration phase of cement and concrete materials [45].

4.1 Kraft fibre processing system and natural fibres

The Kraft pulping process is the largest portion of global pulp production [46]. This process (kraft pulping) is the conversion of wood chips or plant materials into a pulp like fibre mass. The main objective is to remove enough lignin to separate the cellulose fibres. There are three main components of plant matter; lignin, cellulose and hemicellulose [47]. The amorphous component of NFs are the lignin and hemicellulose. These components enhance the strength of the fibres by maintaining unity and agglomeration of fibres [48]. Lignin protects two main polysaccharides used within the plant cell walls that are hemicellulose and cellulose. Lignin binds the proteins to reduce enzymatic depolymerisation including cellulolytic and hemicellulolytic enzymes [49, 50]. Therefore, when the lignin content is reduced the cellulose fibres no longer agglomerate and the dispersion of fibres multiply. Cellulose is the main component of strength and stiffness within NFs. Cellulose is composed of glucose and formed via rigid insoluble micro-fibril chains that are integrated by many intra and intermolecular hydrogen bonds [26, 42, 51]. Hemicellulose surrounds the cellulose chains to strengthen the bond of cellulose components as well as interacting with lignin. The components of natural fibres are shown in Figure 6.

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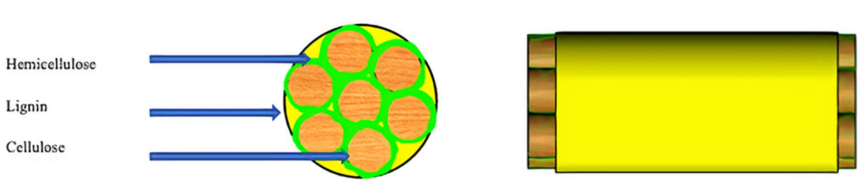

Figure 6 Components of NFs. Redrawn from [52]

The kraft process removes the lignin content via the application of hot chemicals within a pressurised vessel or digester. A mixture of alkaline chemicals that has a pH level above 12 are most effective when cooking at a temperature of 170 °C [53, 54]. Researchers have reported the use of “white liquor” chemicals such as sodium hydroxide (NaOH) and sodium sulphide (Na_2S) used within the processing system [46, 53, 55, 56]. The wood chips or plant materials are ultimately cooking within the chamber while the chemicals are attacking and dissolving the phenolic material (lignin). The dissolvement of lignin is caused by the hydroxide and hydrosulphide anions which cause the components to fragment into water/alkali soluble or hydrophilic fragments. When the material has reached the appropriate temperature and time parameters, the pulp is then washed, screened, cleaned and dried [54]. Figure 7 illustrates the fibres transformation during the kraft process.

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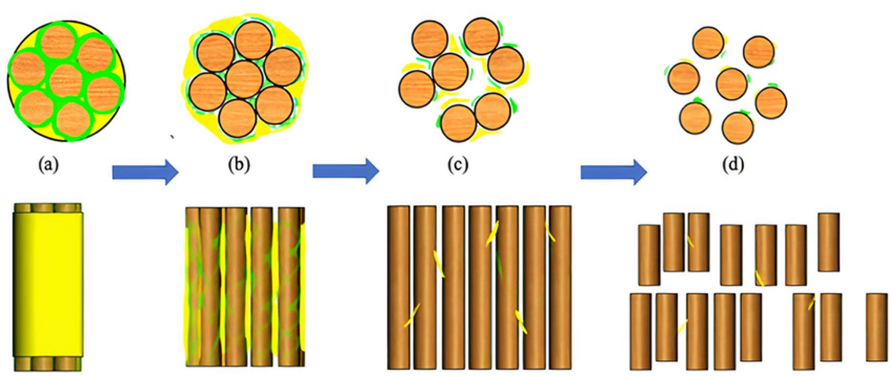

(a) Before kraft processing, (b) Degradation of lignin, (c) Degradation of hemicellulose, (d) Segregation of cellulose fibres

Figure 7 Kraft transformation process of NFs. Redrawn from [52]

To measure the residual lignin content within kraft pulp, the term used within the chemical composition is expressed by “kappa number”. A lower kappa number means less lignin and is measured within a range of 1-100, this is applicable to all varieties of chemical and semi-chemical pulps [55]. The reduction of lignin and hemicellulose during the kraft process results with a rise in concentration of cellulose pulp [57]. Ma et al. [57] noted that the rise in lignin concentration resulted with a reduction in the fibres mechanical properties. Therefore, the lower content of lignin can enhance the fibres mechanical properties.

Research on the integration of NFs within cement-based materials show that degradation caused on the fibres significantly reduces the lignin and hemicellulose content. There are four main collective processes of alkaline deterioration, these include; degradation of lignin, deterioration of hemicellulose, degradation of hydrogen bonding and alkaline hydrolysis of cellulose micro-fibrils [42]. The alkaline attack includes the hydroxide anions in cement pore solution to react with the lignin, which causes the lignin to disintegrate. This reaction then results with the release of phenolic hydroxyl groups, reducing the strength of the agglomeration of hydrogen bonds. During the alkaline attack the hemicellulose components convert into fermentable sugar, increasing the hydrophilicity and therefore enhancing the hydrolysis of lignin and hemicellulose into soluble fragments. The fragments are then separated from the fibres thus in turn reducing the strength and durability of the fibres [42]. Of these components, amorphous properties increase the crystallisation and mineralisation on the fibres, these two factors lead to the reduction of fibre strength, fibre embrittlement and lower strain capacity of the fibre. Bonnet-Masimbert et al. [48] and Kochova et al. [58] discuss the importance of removing hemicellulose, lignin and other surface impurities such as fatty acids, pectin, wax and tyloses. The removal of these constituents can increase the surface roughness of the fibre which leads to a stronger adhesion and bonding within the matrix. It is important to note that the embrittlement of the fibre is highly dependent on the amount of calcium hydroxide ($Ca(OH_2)$) that is within the matrix.

Although the alkaline attack on lignin and hemicellulose components of the fibre can reduce a level of protection against the cement matrix, it can also significantly decrease the water retained in the fibre cell walls. KF already has a significant level of lignin and hemicellulose removed during the kraft process [35, 58]. The removal of these components and other impurities will allow a stronger bond within the matrix, as well as reducing the water retained in the fibre [59]. This is further discussed with Bonnet-Masimbert et al. [48] that use NaOH to pre-treat oil palm fibres, in order to remove the unwanted lignin and hemicellulose properties. The removal of these components allow the cellulose microfibrils to align themselves parallel with the applied load [48]. With this effect, it can enhance the load transfer and increase mechanical properties. This ultimately reduces the spiral angle and increases resistance of the fibre. Table 3 summarises the key differences between KFs and NFs.

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Table 3 Key differences of KF and NF

Factor	KF	NF
Fibre dimensions	Thinner fibres	Thicker fibres
	Shorter fibres	Longer fibres
Fibre coatings	Removal of hemicellulose	Amorphous protection
	Removal of lignin	Fibre impurities (fatty acids, pectin, wax)
Fibre surface	Increased surface roughness	Smoother surface area
	Decreased water retention in fibre walls	Retention of water in fibre walls
Fibre propensity	Dispersion	Agglomeration

4.2 Experimental KF research applications

The advancement towards an environmentally friendly option to fibre composite materials has shown prominent researchers focusing on KFs. Table 4 demonstrates the material matrix, type of KF, pulp ratio and research application. This Table focuses on experimental research that has been conducted due to the desired final application of the material being integrated within building and construction materials. The findings and observations show that the incorporation of pozzolanic materials or admixtures has been a common inclusion within the composite matrix. Rarely has the ratio of fibres exceeded 10%, with the common application as a reinforcement within fibre cement composites. This is further shown in Table 5, where the common experimental method is to measure the flexural strength and ageing process of weathered materials. It is important to note that the predominant research has focused on virgin KFs. With a selected number of researchers focusing on recycled KFs derived from waste materials such as cardboard and paper materials [18, 19, 55, 60, 61]. Despite the recycling process undertaken to retrieve the KF content, the fibres can remain an effective reinforcement agent when integrated within cement-based composite materials.

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Table 4 Overview of the research on applying kraft fibre pulp in cement composites

Matrix	Fibril types	Properties		Reference/s
		Fibre Percentage	**Application**	
OPC- Admixtures	Eucalyptus Kraft pulp	5	Reinforced cement composites	[39, 62]
OPC	Sisal Kraft pulp	4.7	Cement roof tiles	[63]
OPC	Eucalyptus Kraft pulp	10	Reinforced cement composites	[64]
OPC	Pine Kraft pulp	8	Reinforced cement composites	[65]
OPC	Pine Kraft pulp w/ PP	1-3	Mortar	[66]
OPC- pozzolans	Pine Kraft fibres	4	Reinforced cement composites	[38, 67]
OPC- pozzolans	Pine Kraft pulp	0.039-0.23	Fibre sheet cement composites	[68]
OPC	Pine Kraft pulp	4	Fibre cement beams	[41, 69]
OPC- admixtures	Recycled waste Kraft pulp	1-14	Reinforced cement composites	[55]
OPC- admixtures	Recycled waste Kraft pulp w/ glass fibres	4	Reinforced cement composites	[18]
OPC- admixtures	Recycled waste Kraft pulp w/ PP and acrylic fibres	8	Reinforced cement composites	[61]
OPC	Pine Kraft pulp	4	Reinforced cement composites	[70]
OPC- pozzolans	Pine Kraft pulp	2	Concrete	[71]
OPC	Pine Kraft pulp	0.5-2	Concrete and mortar	[45, 72]
OPC	Eucalyptus/ Sisal/ Banana Kraft pulp	4-12	Reinforced cement composites	[60]
OPC- pozzolans	Eucalyptus/ Sisal/ Banana Kraft pulp	4- 12	Reinforced cement composites	[36, 59, 73]
OPC- pozzolans	Sisal/ Pine Kraft pulp	4-12	Reinforced cement composites	[74]
OPC	Eucalyptus Kraft pulp	3	Reinforced cement composites	[75]
OPC- pozzolans	Eucalyptus/ Sisal Kraft pulp	1-5	Cement roof tiles	[76]
OPC- pozzolans	Pine Kraft pulp	8	Reinforced cement composites	[77]
OPC- pozzolans	Eucalyptus Kraft pulp	5-15	Reinforced cement composites	[78]
OPC- admixtures	Pine Kraft pulp	8	Reinforced cement composites	[79]
OPC	Pine Kraft pulp	4	Reinforced cement composites	[80]
OPC	Eucalyptus Kraft pulp	6	Reinforced cement composites	[81]
OPC	Recycled waste Kraft pulp	25-33	Concrete blocks	[19]

Table 5 Testing conducted on kraft fibres

	Mechanical			Physical					Durability				Reference/s
Country of study	Flexural	Compressive	Tensile	Water absorption	Permeable voids/ Porosity	Shrinkage	Thermal	SEM	Wet & dry cycles	Freeze & thaw cycling	Carbonation	Chloride ion	
Brazil	✓			✓	✓			✓	✓				[62]
Brazil	✓			✓	✓			✓	✓		✓		[63]
Brazil	✓			✓									[39]
Brazil	✓							✓	✓				[64]
United States	✓			✓			✓		✓	✓	✓		[65]
United States								✓					[66]
United States	✓						✓	✓	✓				[38]
United States	✓							✓					[68]
United States	✓							✓	✓				[41]
United States	✓								✓				[69]
United States								✓	✓				[67]
Iran	✓							✓					[55]
United Kingdom	✓			✓	✓			✓					[18]
United Kingdom	✓												[61]
Canada	✓	✓						✓	✓	✓			[70]
Canada		✓		✓	✓			✓				✓	[71]
Canada		✓		✓	✓	✓		✓				✓	[72]

Canada		✓				✓		✓			[45]
Brazil	✓			✓	✓			✓			[60]
Brazil	✓			✓				✓			[59]
Brazil	✓							✓			[36]
Brazil	✓			✓	✓						[74]
Brazil	✓			✓				✓			[73]
Brazil	✓							✓			[75]
Brazil	✓			✓	✓		✓		✓		[76]
Brazil	✓			✓	✓		✓	✓	✓	✓	[77]
Brazil	✓			✓	✓			✓			[78]
United States	✓			✓		✓			✓		[79]
Spain	✓	✓						✓	✓		[80]
Brazil	✓			✓	✓		✓	✓	✓	✓	[81]
Pakistan		✓	✓	✓							[19]

5.0 The mechanical performance of Kraft fibre

The following section describes the factors affecting the successful integration of KFs for further use in cement-based composites. As shown in Table 4, researchers have conducted a variety of mix design experiments with the use of KFs as a reinforcement agent and partial cement replacement within cement-based composites. Due to the inter-connected physical and chemical reactivity of OPC and KFs, the mechanical outcome of those experiments has remained hindered. Table 6 highlights the current strengths, weaknesses, opportunities, and threats (SWOT) associated with the use of KFs within a cement-based matrix.

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Table 6 SWOT analysis of KF composites

	Physical	Mechanical
Strengths	Adequate Bonding capacity	Fibres bridge the matrix cracks (reducing larger cracks to smaller)
	Reduce free plastic shrinkage	Adequate stiffness and strength
	Enhanced toughness and impact resistance	Decrease thermal conductivity
	Decrease cement consumption	Increase sound absorption
Weaknesses	Fibre fracture	Reduced long term durability
	High water absorption	Fibre pull out
	Lower fire resistance	Complex matrix requirements
	Fibre mineralisation	
Opportunities	Utilising waste cardboard as a source of fibre reinforcement and cement reduction	The formation of an effective crack bridging system with the use of recycled kraft fibres
	Reducing the stockpile of cardboard waste in landfill	Reducing the weight of concrete composites in certain applications of high-rise buildings
Threats	Economically not a viable solution	Severe environmental conditions can reduce the application commercially
	There are insignificant reductions of CO_2 emissions	The integration of waste fibres with concrete materials is complex and troublesome

Cement composites containing NFs typically fail due to the embrittlement of the fibre and will either snap or the fibre will pull out of the matrix. As the load on the material increases, the composite will reach a maximum bearing capacity. The stress is released immediately to other areas of the composite via the formation of micro cracks, as those micro cracks develop larger, other areas will also begin to form additional micro cracks [55]. This process continues until the merging of the micro cracks happens and creates a visible crack in the material [18]. The cracks will form at mid-span where maximum tensile stresses are applied, reducing the ductility of the composite. The stress loading is called ‘Bend over point’ and as this increase, so does the elongation. The fibres will then be taking the load via a process called crack bridging. The fibres attempt to deflect the failure of that area and transfer the load away from the failing point. However, during the application of maximum stress, fibre pull out is simultaneously occurring. This highlights that the preliminary factor of failure is with the interfacial bond and not the individual properties of the fibre material.

Therefore, it is imperative to enhance the bonding of the material as well as protect the outer layer of the KF from the aggressive nature of an OPC matrix. Fibres that have been immersed in hydrated cement or are within a high alkalinity environment will usually fail due to fibre snapping. However, when the fibres pull out of the matrix, this is due to a less adhesion strength rather than the tensile strength properties of the fibre. The increase of calcium silicate hydrate (C-S-H) can further attach to the surface of the fibres and therefore create a stronger bond of the interfacial fibre zone. Silica fume (SF) has been shown to enhance the C-S-H levels within cement materials [49]. Therefore, a prevalent research area has been with the integration of pozzolanic materials [82]. It has been shown that lowering the density of cement-based composites with pozzolanic materials such as Metakaolin (MK), FA and SF can improve the mechanical properties of fibre composites. This is completed when the short fibres are under implied loads and the crack bridging system is enabled. A denser matrix reduces permeable voids and the load transferability to the fibre reacts at a faster rate [18, 55, 71, 82].

The summary of the discussed thirty one analysed research publications is illustrated in Figure 8. The Figure represents all experimental research conducted on KF cement-based composites. Three parameters were measured of SCM integration, mechanical and durability studies. As discussed in this review, the causation factors of degradation have been thoroughly reviewed. While other areas of experimental research have remained seldom. These areas of research include tensile and compressive strength properties, acoustic and thermal measurements as well as sustainability assessments. Utilising the information within this review can direct future researchers on the development of a comprehensive mix design to mitigate the negative effects currently being created.

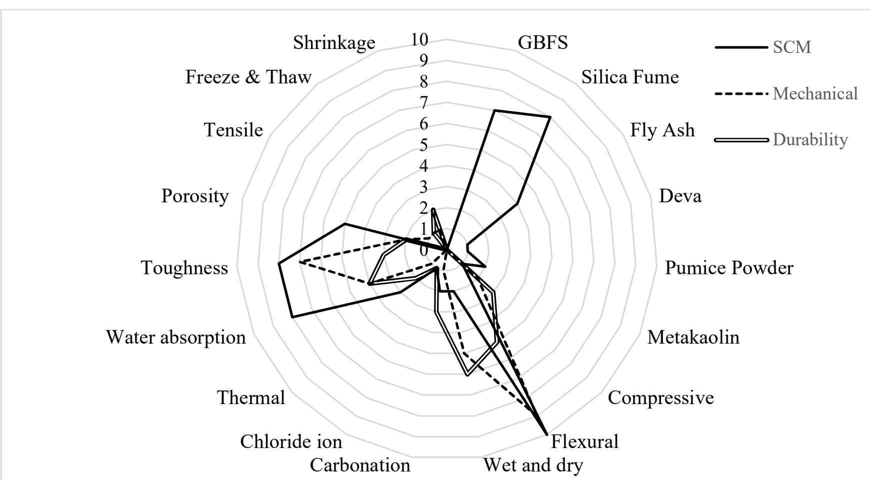

Figure 8 KF analysed experimental research publications

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5.1 Methods to improve composite design

There are two critical elements to maintain the integrity of KFs within cement-based composites. Firstly, to reduce or remove the alkaline compounds. This reduces the degradation that occurs on the cell walls of the fibre, ultimately rendering it weak and ineffective [62]. Secondly, to enhance the stability of the fibres within the cementitious matrix via chemical or physical modification [25]. Incorporating these two modification factors within the mix design of KF cement-based composites will ensure the design life of the material application is maintained to its physical and mechanical requirements. However, the integration of these factors is also limited by several external and internal influences. Examples of external influences include but not limited to weathering conditions, including physical and chemical weathering, location of application, applied loads and forces. These influences can cause the material to deteriorate, accelerating the ageing conditions and significantly weaken the material. Therefore, the primary focus during the mix design is to optimise the internal influences, to inhibit the negative effects caused by external influences. Other materials such as mineral and synthetic fibres are not often affected by external influences due to their hydrophobic nature. This is shown in composite materials containing carbon waste fibres that increase the compressive and flexural strength values by 87% and 113-192% respectively [83]. Researchers have found that integrating KFs with other materials such as polypropylene and acrylic fibres, the mechanical values increase. Khorami et al. [61] show an improved toughness and ductility value when 1.5% acrylic fibres were integrated.

The internal influences include but not limited to are fibre mineralisation, matrix voids, clumping of fibres, fibre percentage and degradation of fibres. A key component when integrating fibres within a composite material is to ensure the fibre dispersion is distributed consistently. The challenging factor is that KFs have a natural tendency to agglomerate and bond together. The different methods of bonding include interdiffusion, mechanical interlocking, capillary forces, coulomb forces, hydrogen bonding and Van der Waals forces. At a single fibre level, the Van der Waals force results with a self-attraction level that is difficult to segregate from other fibres. This agglomeration consequently concludes with the formation of fibre clusters within the matrix [84]. The clusters cause voids, pockets and ultimately an insufficient fibre dispersion. The presence of voids and pockets, creates weak points when under implied loads. The same issue can promote permeability within the matrix, allowing chemical and moisture transference to occur. Reducing the number of voids is critical to decrease the movement of chloride ions in concrete composites, as chloride ions can enhance carbonation as well as the alkali-silica reaction, ultimately reducing the service life of the material [18, 36]. Different materials and chemicals can reduce the clumping of fibres such as SF. Research conducted by Sanchez and Ince [84] show the use of SF separated the fibres due to the small particle size acting as a wedge between carbon nanofibers (CNF). For the composite to remain effective as a reinforcement agent, the fibres must interlock to a certain degree. However, ensuring the dispersion rate is high allows the fibres within the composite to remain effective as a reinforcement agent and take effect during the formation of the crack bridging system [40].

5.2 Fibre modification

Degradation of fibres are due to alkaline hydrolysis and mineralisation of fibre cell walls within OPC matrices [85]. The main cause of high alkalinity is the production of $Ca(OH)_2$ within the OPC matrix. Therefore, reducing the amount of $Ca(OH)_2$ will enhance the longevity of the fibres [25, 36, 86]. With a high volume of $Ca(OH)_2$, the hydrated cement products can attach themselves to the walls of the fibre and mineralisation can begin to form. This process weakens the fibre and results with fibre embrittlement [66]. Therefore, fibre modification is required to enhance the service life of KFs within the cement matrix. A fibre modification via pre-treatment will reduce the degradation caused that renders the fibres weak and brittle. Due to the removal of NFs amorphous components during the kraft process, KFs remain exposed to these two detrimental factors. Therefore, pre-treatment is an important pre-requisite when integrating KFs within a cement matrix. If KFs are not pre-treated, the cellulose micro-fibrils will be stripped apart and the lumen of the fibre will be saturated with cement hydration products [85]. This results with the embrittlement and failure of the fibre to act as a reinforcement agent. There are several methods of pre-treatment including silane coatings, hornification, autoclave, thermal treatment and chemical treatment [42, 62, 64, 69, 79-81, 87].

Methods of pre-treatment can include diluting a chemical admixture with water before the application of fibres. This ensures the aqueous solution does not clump or stick to specific areas of the fibre material. Often, the fibres are oven dried before application within the matrix to ensure no condensation remains on the fibre and moisture is completely removed before application [87]. If water is to remain on the fibres it can create an over-supply of moisture within the matrix and can further result with voids, creating an excess in permeability. Dittenber and GangaRao [26] show an improved bond within the matrix can be achieved with prior drying of fibres before application. The hydroxyl groups on the fibre will bond with hydroxyl groups within the matrix, creating hydrogen bonds. This results with water molecules bonding with the hydroxyl groups on the fibre surface, as the water evaporates it can create voids within the matrix, resulting with an ineffective fibre bond. This factor creates a weaker matrix and reduces the bonding between the interfacial zone of the fibre and the matrix of the composite.

Fibre modification has been shown to enhance the interfacial bonding between the fibres and composite matrix [72]. This results in the ability to transfer loads within the composite microstructure when axial loading is applied. Recent studies of concrete composites containing KFs resulted in a reduction in mechanical compressive strength. However, the fibres included unmodified fibres (UF), mechanically modified fibres (MMF) and chemically treated fibres (CTF). When fibres have been modified there is an increased fibre density, resulting with composite compressive strength similar to samples without fibre reinforcement. When fibres weren't modified there was a larger reduction in compressive strength at 28 and 90 days, equalling 28.9% and 17.4% respectively. The increased density of composite materials has shown improved mechanical properties [72]. Previous studies also indicated a reduction in compressive strength due to the integration of KFs [45, 70-72]. Research studies with MMFs and CTFs in mortar cubes show a less compressive strength reduction than UFs. Although there is a reduction in compressive strength, samples that contained 4% by weight of cement with UFs showed the largest reduction in strength of 25% when compared to the control sample containing zero fibre integration [70]. This suggests that the UFs do not contain a sufficient fibre matrix bond when compared to modified fibres. When fibre bonding is enhanced, there is an improved load transfer within the microstructure of the matrix. However, other research involving the hornification process of KFs show a 7% increase of compressive strength and 8% increase in flexural properties [80]. KFs have a lower density when compared to other synthetic materials and are expected to induce more voids, rendering a lighter composite [18]. When fibre modification is applied, the voids are reduced, increasing the compressive and flexural strength values.

Other methods of thermal fibre modification were performed by Mohr et al. [67, 69]. Their research integrated kraft thermomechanical pulp (TMP) within cement-based composite designs. The results demonstrated TMP exhibits increased first crack strength when subjected to flexural testing due to the micro crack bridging system. However, in the post cracking region of the composite, the strength and toughness decreased. This can be further attributed to the cellulose content of TMP (40- 45%) when compared to cellulose content of other KFs (65- 80%). When there is less cellulose content, the tensile strength of the composite decreases, and fibre pull out occurs at a higher rate. Tensile strength of TMP is approximately 50- 70% of KFs [69]. TMP exhibits a slower degradation when subjected to wet and dry cycles when compared to unbleached and bleached KFs. This is further shown with increased flexural strength of 77.1% and 85.7% and increased toughness properties between 138.6% and 221.7%, respectively, after 25 wet and dry cycles. This research highlights the significance fibre modification can have on composite designs.

When fibres are not modified there is an increased composite porosity, lower mechanical values and a reduction of durability [18]. However, despite these factors, the integration of KFs within a cement-based composite will enhance the flexural properties of the material. Savastano et al. [60] has shown the integration of 12% fibre content by mass, results with flexural strength values between 20MPa-25MPa. These values correlate further with fracture toughness results between 1.0- 1.5kJ m^{-2}. Composites containing zero fibre content withhold approximately 12MPa and 0.5 kJ m^{-2}, respectively. Although, the values are significantly enhanced, the long-term durability of the composite is hindered by the ability of the composite to withhold moisture and deflect the high alkalinity. Composites containing similar values of fibre content (12%) have a water absorption ability of more than double when compared to zero fibre composites. As previously discussed, this factor can lead to severe degradation when water evaporates. Therefore, modified fibres withhold a significant influence on the microstructure of composite materials. This is shown with an enhanced fibre matrix interfacial zone and reduction in mineralisation of the fibre [62]. The results of fibre modification are shown in Figure 9. This Figure represents current literature that has used various fibre modification techniques to enhance the composites mechanical properties.

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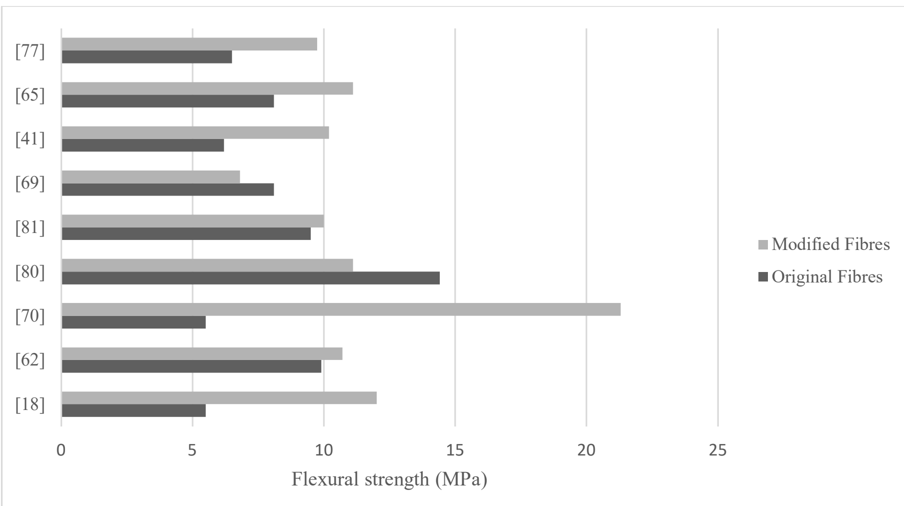

Figure 9 Flexural properties of modified fibres vs. original fibres

5.3 Matrix modification

As discussed, OPC contains a high amount of $Ca(OH)_2$ and this factor attributes to the degradation of KFs [38]. It has been shown that reducing the amount of $Ca(OH)_2$ can mitigate the degradation and enhance the materials composition [52, 85]. An effective and common approach is to integrate the use of SCMs [25, 38]. When modification of the cement matrix is required, the integration of SCMs can lead to enhanced mechanical properties, lower costs and positive environmental impacts [42]. The environmental benefits include a reduction in CO_2 and greenhouse gas emissions, which has lead to the United Arab Emirates mandating the use of SCMs within concrete materials [88]. The integration of SCMs can enhance the service life of final application and reduce the damage of corrosion that typically happens within traditional concrete. Moreover, SCMs are a sustainable answer to reduce the adverse effects caused by the clinker factor of cement. The integration of industrialised by-products such as SF, GBFS and FA can aid in the accumulation of that waste further within cement-based materials [42].

Significant research has been studied on the integration of various SCMs because of their pozzolanic properties [38]. SCMs contain two notable integration characteristics: First, a positive influence on the hydration kinetics of OPC and secondly, a considerable consumption of $Ca(OH)_2$. The natural pozzolanic property within SCMs are an attractive supplement due to the conversion properties of $Ca(OH)_2$, into a desirable product called C-S-H [89]. The chemical properties can counterattack the aggressiveness of the high alkalinity within cement paste. A finely ground pozzolan material primarily consists of siliceous or aluminous, that when in the presence of moisture chemically reacts with $Ca(OH)_2$ to form cementitious properties. The pH level of cement is approximately 12-13, which is high alkaline [42]. Therefore, integrating an appropriate SCM will reduce the pH level and create an enhanced environment for KFs to remain effective.

The most commonly used SCMs include; MK, SF, GBFS and FA [88]. Several researchers have used these materials within research of composite designs due to the improved mechanical properties [38, 78, 85]. For example, Machado et al. [78] has shown the presence of SF can create a greater amount of hydrated calcium silicate, which aids in the strength of the composite as well as increases the service life when exposed to weathering. However, the researchers noted that when excessive amounts of SF (17.1%) and high values of cellulose fibre (13.5%) are integrated, the porosity of the composite also increases. This can be attributed to the hydrophilic nature of the fibre and the heterogeneous dispersion of SF within the design mix. SF can act as a filler and reduce the porosity of a composite, minimising voids that contain air and moisture [77]. However, the measurement of the materials integration is critical, as excessive amounts can enhance water absorption and reduce durability [78]. Moreover, Machado et al. showed when 10% SF and 10% fibre was integrated, the modulus of rupture (MOR) and modulus of elasticity (MOE) had maximum values at both 28 and 180 days. The results were 12.16-12.48 and 18.15- 17.64 MPa respectively. When SF increased, the MOR and MOE significantly decreased at all ages. This further highlights the importance of controlled levels of SCM incorporation. Other results of SF and limestone powder integration have increased MOR to 8.5MPa. This is a flexural increase of 260% [55]. It is important to note that the flexural strength is marginally improved when SF is integrated, however the critical dimension that SF improves is compressive strength.

The ability for the fibre to maintain its strength is dependent on the applied matrix. For example, GBFS can alter the composites matrix by altering the chemical composition. This is shown with a reduction of Ca(OH)2 as compared to OPC. This factor should increase the fibres ability to withhold its mechanical strength. However, research incorporating the integration of GBFS has shown reductions in the fibre composites flexural capacity [36, 73]. This is discussed with Savastano et al. [74], that shows a high porosity within the microstructure of the composite. When GBFS is used within the material, there are values of at least 30% water absorption by mass of the composite. Due to the high porosity of the microstructure, effective crack bridging systems can remain inactive leading to severe reductions in mechanical properties [73]. OPC composite mix designs with KF integration can have sufficient mechanical values, however, the service life and durability of the composite will be severely reduced. The discussed maximum flexural values are illustrated in Figure 10. This Figure represents materials containing an age of 28 days, with higher MOR values often containing SCM integration.

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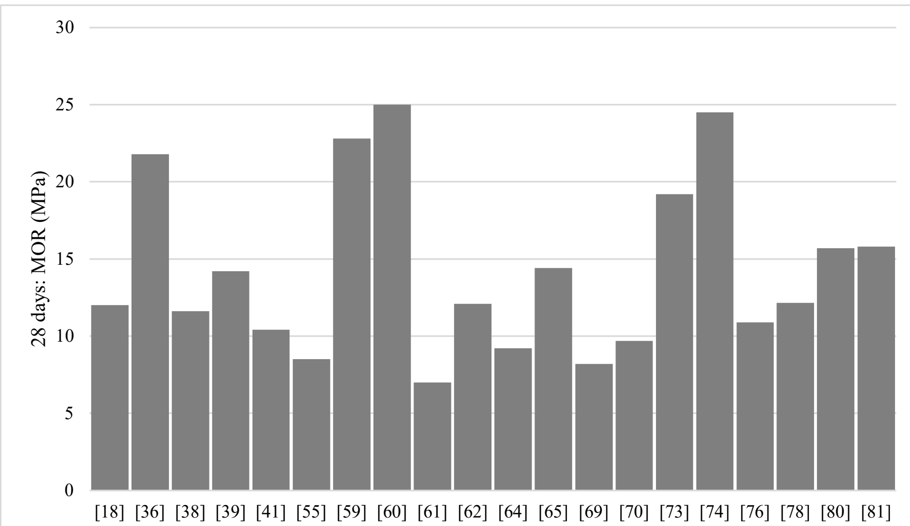

Figure 10 Mechanical values of Kraft fibre composites

6.0 Durability enhancement

6.1 Fibre modification

Without fibre modification, hydrated cement products attach themselves to the walls of the fibre and mineralisation begins to form. This process weakens the fibre and causes embrittlement to the fibre walls [38]. Soroushian et al. [65] highlighted petrification can advance due to accelerated ageing cycles. Their research showed that when hydrated cement products fill the fibre cell wall cavities, there is an increase of fibre rupture at fracture surfaces. However, the repetition of wetting-drying cycles increased the flexural stiffness but reduced the flexural toughness without significantly affecting the flexural strength of the composite. Although the results were mixed for freeze-thaw cycles, the outcome on flexural strength was similar. It can be suggested with the integration of SF, there was an increased C-S-H content, causing enhanced durability with the flexural properties of the aged composites. Their research signifies the importance of a combined fibre and matrix modification. Other research conducted by Dittenber and GangaRao [26] show that an improved bond within the matrix can be due to prior drying of fibres before application. Hydroxyl groups on the fibres will bond with hydroxyl groups within the matrix, creating hydrogen bonds. This results with the water molecules bonding with the hydroxyl groups on the fibre surfaces, as the water evaporates it creates voids within the matrix and the fibres bonding decreases. Therefore, drying of the fibres will result with improved bonding due to the elimination of the hydroxyl groups.

As discussed, fibre modification has been shown to increase the durability of KFs when applied within a cement-based composite. Booya et al. [72] show the effectiveness on the durability properties of MMFs and CTFs in contrast to UFs. Due to the long service life of concrete structures, the chloride ion penetration test can assist in evaluating the durability of the material. The less charge passed through the material indicates a better quality of concrete and increased service life. The research findings showed a higher charge of coulombs passed through the composite material when it contained UFs, this results with a lower material durability. The tests subsequently indicated that MMFs and CTFs had a lower charge passed through when compared with UFs. Moreover, the increased chloride ion permeability of UF concrete composites is due to a higher value of interfacial porosity between the fibre and interfacial zone of the matrix [72]. These results were in accordance with other durability testing such as sorptivity index and water absorption. The researchers demonstrated that modified fibres were superior than UFs, when applied in KF concrete composites [71]. Other research of TMP have shown an increased durability within composite designs [69]. This is shown with results derived from wet and dry cycles, indicating that the flexural strength and toughness are superior to UFs. Moreover, when fibres are subjected to modification, the dimensional stability is enhanced but also the mitigation of cement hydration products attaching to the fibre walls. These two factors allow the fibre to maintain its strength [67].

A common durability testing method of composite materials is with the inclusion of wet and dry cycles [65, 70, 79-81]. This method accelerates the environmental effects that can be imposed on composite materials. When KF composites are subjected to wet and dry cycles, the flexural strength and toughness of the composite are substantially reduced [70]. This is due to the reduced fibre strain capacity. However, modified fibres have shown enhanced mechanical and durability properties. This suggests that the cell wall mineralisation of the fibre was minimised, ultimately increasing the strain capacity of the fibre [42, 70]. Booya et al. [70] showed similar flexural strength properties of CTFs after 30 wet and dry cycles (approximately 5.7MPa). The researchers demonstrated the increased strain capacity when surface modification has been applied to KFs. Overall, from zero to forty cycles, the reduction in flexural strength was shown as 49%, 43% and 33% when composites contained UFs, MMFs, and CTFs respectively. These results also correlate with a reduction in the flexural toughness, 76.6%, 50.1% and 42% for composites containing UFs, MMFs and CTFs respectively. Moreover, when fibres have been modified, there is a greater volume stability of the fibre due to the refinement and pre-treatment process [70, 81]. The modification of fibres shows a reduction of migrated hydration products within the fibre lumen, predominantly calcium hydroxide $Ca(OH)_2$ [67, 69]. Ballesteros et al. [81] have shown the dimensional stability of fibres with hornification treatment. Hornification of KFs show an enhanced fibre matrix interface with a greater specific energy of the composite design [80]. Reducing the percentage of water retained within the fibre, resulted with an increased fibre anchorage system within the matrix. When fibre modification has not been applied, composites containing KFs can significantly absorb water, reducing the durability. This has been shown with Savastano et al. [60] that conducted research using 12% fibre content. Their results demonstrated water absorption had more than doubled. Moreover, due to fibre modification increasing the interfacial zone of the fibre within the matrix, the durability and flexural properties increased [80]. This also in accordance with other researchers that show increased mechanical benefits when fibre modification is applied [45, 70-72, 79, 80].

Freeze and thaw cycles have been shown to alter the fibre bond when compared to wet and dry cycles [65, 70]. When axial pressure is applied on the composite, fibre rupture is caused rather than fibre pull out [70]. This is because of an excessive fibre matrix bond within the microstructure of the composite. Flexural strength decreases from zero to forty cycles with reduction results of 20.5%, 23.9% and 29.6% for composites containing UFs, MMFs and CTFs respectively. However, when the results are compared to forty cycles and unaged specimens the reduction shown is 19.5%, 1% and 1% for composites containing UFs, MMFs and CTFs. MMFs contained the better flexural performance when compared to UFs and CTFs. However, the decrease in flexural strength remained the same after ten cycles for CTFs. The freeze and thaw cycles show an increased resistance of flexural strength and toughness when compared to the wet and dry cycling. Researchers have suggested the durability is increased due to the initial resistance of micro-cracks by internal frost pressure [65, 70]. Therefore, an increased resistance to freeze and thaw cycles have been shown with modified fibres when compared to UFs.

6.2 Matrix modification

Modifying the matrix of composite designs can aid in the service life of the material [38]. Reducing the level of alkalinity within the matrix can ultimately enhance the durability of the fibre in the composite material. Machado et al. [78] have integrated SF and natural rubber latex to increase the durability properties of KF composites. The results showed that the materials increased fibre strength and prevention of hydration products on the walls of the fibre after 180 days. Moreover, the added effect of carbonation decreased the porosity and permeability. This increased the durability by reducing the water absorption of the composite. These results are in accordance with Urrea-Ceferino et al. [77] who showed the effects of accelerated carbonation on samples with silica as the mineral supplement. After 200 dry and soak cycles, the KF composites exhibited similar MOR measurements than compared with nonaged specimens. This was shown with results of 6.49 MPa- 10.9MPa, and 6.17MPa- 9.39MPa, respectively. The researchers concluded that the mechanical properties were maintained due to the use of silica as an inert filler. It is important to note that the integrity of mechanical values coincides with the durability characteristics of the composite. This conclusion is in accordance with Mohr et al. [38] that conducted durability studies with SCM composite integration. Their research concluded that SF replacements of

30% or more can eliminate degradation caused on the fibre due to wet/ dry cycling. This is shown with the flexural properties after 25 cycles, 30 and 50% SF composite contained maximum strength values of 200.4% and 159.4% respectively. However, prior to wet and dry cycling only 50% SF composite had similar post cracking toughness to the control. Where 10% and 30% SF composites had 35.4% and 27.4% lower values in toughness respectively. These results are in accordance with Machado et al. [78] that discussed the increase of SF content can increase the porosity of the material, reducing composite toughness. Although the results of SF incorporation are significant, the economic viability is burdened [38].

The benefit of SCM integration can be a denser matrix that can reduces voids and permeability within the composite design [18, 55]. This is shown to reduce fibre pull out while minimising water and moisture movement. When the matrix is permeable, chloride ions can integrate faster causing a higher rate of carbonation in concrete composites. However, the integration of KFs can bind chloride ions and prevent the progression throughout concrete. This prevention is a result of the microstructural permeable pores created because of the fibres. This enhances the prevention of corrosion and spalling within concrete applications [72]. Due to the hydrophilic nature of KFs, it is expected that there would be a higher water absorption within the mix and therefore reduce the cracks formed from plastic shrinkage. Booya et al. [71] incorporated SCMs to mitigate the loss of compressive strength within concrete KF composites. KFs were integrated with SCMs including FA, MK, SF, Pumice powder and GBFS. The compressive strength was measured before and after the addition of SCMs, with MK achieving the highest compressive strength at all ages of testing. It is important to note that the replacement value of cement with SCMs was 10%. There was also a significant reduction in permeability with MK and SF due to the transformation of large pores into fine pores. This was shown to be caused by the pozzolanic reaction between MK and SF during early hydration, resulting with a denser composite.

A benefit of reducing the sorptivity index with matrix modifications can be shown with the increased durability of the composite material. This has been shown in KF concrete composites with the integration of SCMs [71]. Cellulose fibres are known to absorb water and cause fibre detachment and microcracks within the composite matrix when the water or moisture evaporates. However, when fibres have been modified this factor reduces. When integrating SCMs such as SF or MK, the sorptivity index reduces showing a reduction of 5-15% and 6-16% respectively. However, the integration of FA, GBFS and Pumice powder showed an increased sorptivity with only GBFS showing a reduction in the first 28 days. These results correspond with the water immersion tests also carried out by the researchers [71]. The effect of GBFS integrated with KFs has also been shown in the study by Roma et al. [76] who highlighted a severe reduction in mechanical and durability properties due to the alkaline attack and petrification of fibres. This led to progressive micro-cracks and a reduction in composite toughness.

Their research demonstrates that GBFS is not as effective to other SCMs when reducing the degradation caused on KF composites. This is demonstrated with a decrease in first crack strength after 1 wet and dry cycle, containing 10-70% GBFS [38]. The mechanical properties are also hindered prior to wet and dry cycling experiments, with composites showing a 23.3- 27.3% decrease in flexural strength. However, composites containing 90% GBFS showed similar mechanical and durability properties. The results were similar even after 25 wet and dry cycles. Although the results of high GBFS content appears promising, the microstructure of the composites has not been significantly discussed [38]. Other research studies conducted by Savastano et al. [59] have shown the high integration of GBFS can lead to a severe lowering of flexural strength (13MPa - 17MPa) in aged composites when compared to OPC KF composites. The researchers discussed there was an increased level of carbonation followed by leaching and progressive microcrack formations in the composite when using GBFS as a cement replacement.

Other matrix modifications using FA have shown mixed results. Increasing the FA content in the composite design has shown decreases in flexural and durability properties subjected to wet and dry cycling. On the contrary, as the amount of FA increases, the composite toughness increases with wet and dry cycling [38]. Other FA composite research [68] show negligible results when FA is included in the design mix. MK integration has been used as a SCM matrix modifier. The durability properties when 30% MK is integrated is comparable to the control. Initially, after one wet and dry cycle, MK exhibits 56.3% flexural increase. However, after 25 cycles, the material then performs similar to the control. This could be due to the consumption of $Ca(OH)_2$ in early hydration as compared to other materials. Although there is an initial increase of strength when subjected to wet and dry cycles, only after 15 cycles there was a steady reduction [38]. Although MK is not a common SCM that is integrated within KF composites, the material is becoming more commercially used due to the effective mechanical and environmental benefits [88].

Matrix modifications have been shown to enhance the fibres longevity within a composite design. This is further shown when no matrix modifications have occurred and there is a significant decline in mechanical properties as the ageing process continues [60]. Tonoli et al. [64] demonstrates this mechanical failure when using refined KFs. Other research [75] demonstrates the acceleration of fibre absorbing chemical properties such as, C-S-H, portlandite and calcite phases. It was shown that when no modification has occurred, the KFs induce the loss of their reinforcement capacity. Therefore, as the research suggests, further exploration of an effective mix design is required to mitigate the common findings found within the literature. A graphical illustration of flexural and compressive values of composites containing SCM integration are shown in Figure 11 MPa values of flexural and compressive strength for composites based on SCM integration

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These values were obtained by measurement of strength for 28 days hardened composite with different levels of SCM components.

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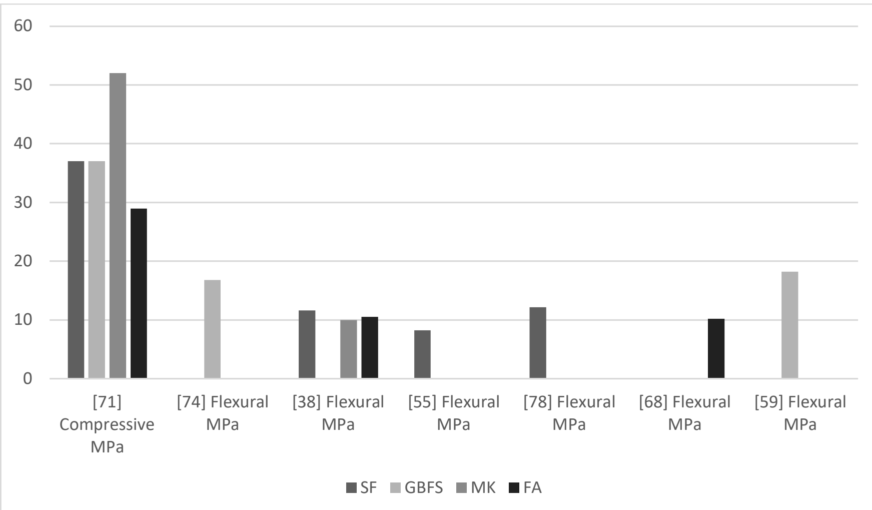

Figure 11 MPa values of flexural and compressive strength for composites based on SCM integration

7.0 Conclusion, limitations, and future research

The building and construction industry has been a leading contributor to the generation of waste materials. The key materials used across the entire industry are concrete and cement-based products. The extraction of virgin materials to produce these products, creates significant environmental burdens and depletes important resources. The use of waste materials to substitute varying amount of cement percentages have been a research focus for many years. However, not all waste materials have been optimised to their full potential. So far, the valorisation of cardboard and paper waste have been relatively unexplored with minimal integration toward the building and construction industry.

The findings within this current study aimed to review waste fibres used within building and construction and cement/ concrete applications. Initially, a bibliometric analysis was conducted to identify research focus areas of waste fibre materials used in the building construction industry. The bibliometric analysis reviewed 874 documents from the year 2000-2020. The results highlighted influential journal sources with a measured growth in the research focused areas. The results demonstrated key words associated with the reviewed articles and sources, allowing the reader to identify waste research focus areas. These findings can allow future researchers to easily identify current research focus areas and research gaps. Future researchers can review these factors and minimise their search analysis to provide thorough assessments for their results and findings. The limitations and assumptions within this review are:

- The review focused on research conducted within the last two decades. Further findings could be identified from a larger timescale.
- The findings from the bibliometric assessment indicated studies on cardboard waste remained seldom. This was conducted through the Web of Science "WoS" search engine. Other search engines could withhold different studies on the topic of research.
- The review focused on utilising cardboard waste within cement-based materials. There could be other studies using the waste source within polymeric materials.

Despite these limitations, the findings from the analysed articles indicated that an optimised mix design has not been thoroughly evaluated to reduce the degradation caused on the fibres. Currently, researchers have provided critical information demonstrating the causation of mechanical and durability reductions when virgin KFs are applied within a cement-based environment. However, only five research articles have sourced KFs from cardboard waste materials. The current study highlights the need to explore other avenues of fibre and matrix modifications via experimental analysis to overcome the key areas of material degradation. This will enhance the ability to source KFs from other avenues such as cardboard waste to be further used in the building and construction industry.

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