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Abstract

Global population growth around the world requires significant infrastructure and building developments. The building and construction industry uses excessive quantities of virgin resources for those developments as well as contributing to the waste generated from the residential and commercial sectors. A contemporary solution is required to reduce these negative environmental impacts. In this study, the mechanical properties of cement composites containing kraft fibres (KFs) derived from waste cardboard was experimentally investigated. KFs and metakaolin (MK) were integrated within concrete samples as a cement substitute material. The compressive, flexural, and tensile strength was determined on three mix designs containing 5% raw KFs, 5% surface modified KFs, and matrix modified concrete specimens. Silica fume (SF) was applied to the fibre walls as fibre modification to lower the alkaline zone around the fibre within the cementitious matrix. 5% MK was used as a partial cement substitute to lower the alkaline level of concrete samples. All KF concrete specimens exhibited lower compressive strength properties. However, MK modified samples exhibited the highest tensile strength of 11MPa. Fibre modified samples had stronger compressive and tensile strength of 20 and 9MPa, compared to raw KFs. However, raw KFs exhibited a higher flexural strength of 2.5MPa. The compressive, tensile, and flexural strength of the control were 25, 10 and 2.6MPa, respectively. Scanning electron microscopy (SEM) observations demonstrated sufficient SF adhesion on the fibre walls, while the energy dispersive x-ray spectroscopy (EDS) observations showed efficient dispersion of all composite materials.

Keywords: Cardboard waste; cement replacement; concrete composites; kraft fibres; Silica Fume; Metakaolin

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1.0 Introduction

In recent years, growing climate awareness has placed significant attention on the use of environmentally friendly materials within the building and construction industry [1]. Alternative solutions are required that offer eco-friendly techniques and processes to minimise the impacts of construction on the environment. Researchers have focused on the integration of waste within building materials as a possible solution to aid in the reduction of landfill and resource extraction [2-5]. This method provides a contemporary solution to reduce the burden on the environment and move towards a circular economy [6, 7].

Over the past few decades, research studies have focused extensively on experimental investigations using waste materials such as glass, fly ash (FA), plastics, tyres, and demolition waste [2, 8, 9]. Integration of glass, tyres and plastics were heavily researched on road asphalt pavement construction and bitumen applications [10-12], whereas FA was predominantly integrated in concrete applications [2, 5, 8, 12-15]. Following glass and plastic, cardboard utilises the most volumetric space in the residential recycle bin [16]. In 2018-19, Australia collected 5.9 million tonnes of cardboard waste and with current waste export restrictions to China, the nation is exploring wide range applications of reusing cardboard waste effectively [17]. Minimising the accumulation of cardboard waste will significantly reduce the burden of landfill management. Currently, there is approximately 270 million tonnes of paper and cardboard waste landfilled within Australia [17]. Reducing the addition of these materials to landfill is an urgent requirement.

Kraft fibres (KFs) are the main constituent of cardboard material which are natural fibres (NFs) containing cellulose matter that provide strength in plants and trees [18]. Use of NFs have attracted the attention of researchers due to their renewability and reduced global warming impacts when compared to the use of synthetic fibres [19-23]. NFs also possess other advantages such as non-hazardous, non-abrasive, biodegradability, high strength, low density and low costs [24]. Recent research studies of KFs focused on partial cement substitution within fibre cement boards, however, the application was not commercially adopted due to the reduced mechanical effects [25-30]. Other materials that were researched as a partial cement replacement included the use of FA, glass powder, ceramic waste, wood ash, ground blast furnace slag (GBFS) and waste tyres [13, 31-35]. Researchers have also investigated supplementary cementitious materials (SCMs) due to the reduction of carbon dioxide (CO_2) emissions and energy consumption in concrete. SCMs have also been shown to improve the strength properties of concrete, reduce the high alkaline levels and lower cement requirements [36, 37]. The production of cement contributes significantly to negative environmental impacts, therefore, reducing the cement content in concrete applications has been of research significance. The effect on the environment from cement manufacturing include excessive natural resource depletion, intense energy demands, air, and water pollution. Cement manufacturing industry accounts for significant energy consumption and is responsible for approximately 5% of worldwide annual greenhouse gas emissions [38]. Therefore, to reduce the burden of cement consumption, a contemporary solution is required. To successfully integrate KFs within cement-based composites, an exploration of matrix and surface modification is essential [39]. This is due to the high alkaline percentage of composites during cement usage. Researchers have stated that high alkalinity levels can cause severe degradation to the fibre wall of KFs

[4, 24, 25, 39-46]. The degradation process can make the fibre weak and brittle, ultimately reducing the service life of the composite application.

To reduce alkaline percentage within cement-based composites, inclusion of various SCMs such as FA, GBFS, Metakaolin (MK) and Silica Fume (SF) were researched [47-50]. These materials have proved effective as a partial cement replacement when used within KF composites; however, the service life is always reduced due to the adverse effects caused on the KFs. The successful integration of KFs within cement-based composites are dependent on the ability to reduce calcium hydroxide ($Ca(OH)_2$) attacking the fibre walls. Reducing the amount of $Ca(OH)_2$ contained will enhance the service life of the application. MK contains a higher percentage of aluminate (Al_2O_3) than other SCMs and has been shown to enhance the hydration of cement in early ages. This is due to the large generation of heat caused by the rapid conversion of Al_2O_3 within the first few minutes. Several researchers [24, 39, 51, 52] included 10- 50% MK substitution with Ordinary Portland Cement (OPC), showing an enhanced durability of NFs. The rapid consumption of $Ca(OH)_2$ reduces the high alkaline percentage that attacks the fibre walls. When compared to FA, GBFS, SF and pumice powder, Booya et al. [24] demonstrates values of 10% MK substitution with OPC can achieve increased mechanical strength while also lowering water absorption and chloride ion permeability. MK was shown to be the most effective SCM as a cement replacement when used in conjunction with NFs [39, 52].

Integration of SF with NF cement-based composites was used to increase durability, workability, compressive and flexural strength [24, 30, 39, 51-56]. An increased percentage replacement of SF showed significant compressive strength improvements, especially after wet and dry cycling analysis. 30% and 50% SF showed flexural strength improvements of 200.4% and 159.4% respectively [39]. Mohr et al. [39] noted that 30% or more SF can reduce degradation of NFs significantly, this is in accordance with the findings in [54]. However, large percentages of SF can reduce workability and increase costs. SF can enhance the formation of calcium silicate hydrate (C-S-H). This occurs with the reaction of $Ca(OH)_2$ crystals formed from hydration of calcium silicates, further increasing the production of C-S-H [56]. This can increase the strength of composite materials and enhance the bond between the fibres and matrix. SF has a high silicate dioxide (SiO_2) content, that consumes $Ca(OH)_2$ at later stages, however, as mentioned KFs require the consumption of $Ca(OH)_2$ rapidly to mitigate the degradation. Therefore, to counter the degradation caused on KFs, materials must be selected that can mitigate $Ca(OH)_2$ at both early and later stages during hydration. For this reason, MK and SF have been selected as most suitable for this study.

This paper presents an investigation of the mechanical performance of concrete when waste cardboard has been integrated in the design mix. The findings demonstrate the effect when both matrix modification and surface modification of the KFs has occurred using MK and SF respectively. The compressive, flexural, and tensile properties are measured over the 7, 14 and 28-day period. In addition, the microstructure of the various mix designs are examined using scanning electron microscopy (SEM) to comprehensively analyse the variation in strength of the composite designs.

2.0 Experimental procedure

2.1 Raw Materials and preparation

Waste corrugated cardboard and MK are the main constituent materials used to reduce the consumption of OPC within the mix design of the concrete specimens herein. Waste cardboard was reduced to a pulp material then combined with SF as a wet slurry to create Silica Fume Kraft Fibre (SFKF). This method is graphically depicted in Figure 1. The moisture is removed from the SFKF via a conventional oven at 20°C for 8 hours. SFKF is then subjected to rotation within a blender mixer. The result is a fibrous material that can be integrated within the concrete mixture. The SF applied to the KFs conforms with the Australian Standard AS/NZS 3582.3 [57] specification of Silica Fume used in cementitious mixtures. MK is used at a 5% percentage level in conjunction with 5% SFKF. The MK used conforms with the ATSM C-618 [58], Class N specifications for natural and calcined pozzolans. OPC is used as the primary constituent for the pozzolanic reactivity of the concrete specimens. The material conforms with AS/NZS 3972 [59]. The composition of the materials is further shown in Table 1. Locally available coarse and fine aggregate were applied, conforming to AS/NZS 1141.6.2 [60] and AS/NZS 1141.5 [61] respectively. Regular portable tap water was used throughout the preparation of the experimental mix design.

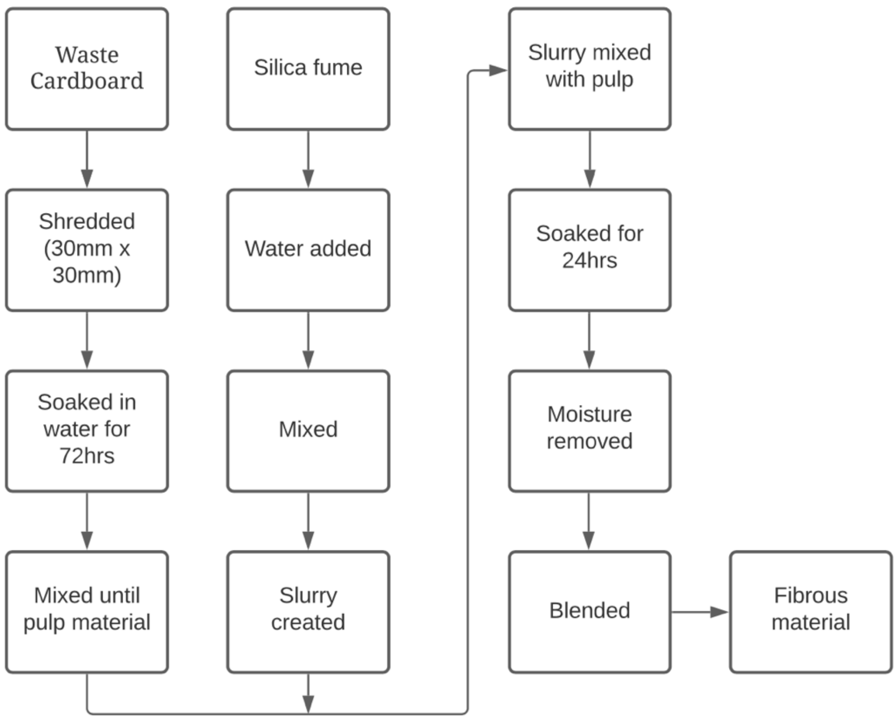


Figure 1 Methodology of SFKF

Table 1 Chemical composition of pozzolanic materials

Chemical	Material component %		
	MK	SF	OPC
SiO_2	54-56	>= 75- <100	19-23
Al_2O_3	40-42		2.5-6
Fe_2O_3	<1.4		
TiO_2	<3.0		
SO_4	<0.05		
P_2O_5	<0.2		
CaO	<0.1		61-67
MgO	<0.1		
Na_2O	<0.05		
K_2O	<0.4		
L.O.I.	<1.0		
Silica, amorphous, fumed, cryst. -free		>=0.3- <1	
$CaSO_4.2H_2O$			3-8
$CaCO_3$			0- 7.5
Fe_2O_3			0-6
SO_3			1.5-4.5

2.2 Mix designs

For all concrete mix designs, the target compressive strength was 25MPa. This is shown to be a primary strength requirement of concrete material applications within Australian residential construction [62]. To comprehensively analyse the reduction of OPC when integrating MK and SFKF, multiple mix designs are formulated as shown in Table 2. Water, fine and coarse aggregates remained the same throughout the various designs with a mass ratio of 0.33, 1.15 and 1.73 per kilogram of concrete respectively. Fibre investigation of SFKF ascertained the effect of fibre modification within the cement matrix. KFs without modification were also investigated to understand the effect of SF on the fibre walls. 5% MK was included to reduce the overall OPC quantity. The mix code is described with the type of fibre, fibre percentage and MK content. For example, SFKF55 correlates to SFKF as the fibre, 5 is the percentage of fibre and 5 is the percentage of MK. When MK is not used in the mix design, only the fibre type and percentage is present, this is shown in KF5 for example. KF corresponds with raw kraft fibre and 5 is the percentage of fibre in the mix design. Current research findings [29, 30] demonstrate a 2-8% optimisation of fibre content within concrete and mortar specimens. Their findings discussed the workability of the specimens are compromised when excessive fibre content is within the design mix. Therefore, 5% fibre integration has been conservatively chosen to reduce the negative effects of the KFs within the cementitious matrix. It is important to note that the water ratio remained the same throughout all mix designs. Researchers [63] have recommended to increase their water content to accommodate the increase of fibre integration. However, due to the low fibre content of this research, water absorption rate of fibres was deemed negligible.

Table 2 Mix design percentage of altered materials

% of OPC reduction design materials

Mix code	OPC	MK	SFKF	KF
Control	100	-	-	-
SFKF55	90	5	5	-
SFKF5	95	-	5	-
KF5	95	-	-	5

2.3 Specimen preparation and curing

The raw materials were mixed using a standard cement or concrete mixer. The materials were dry mixed for 5 minutes before adding water. This allows sufficient agglomeration of all materials. After adding water, the materials were mixed for an additional 5 minutes. Upon completion of mixing, the concrete was added to the various moulds in three layers. A steel rod was used to compress the materials twenty times before the additional layers were added to the mould. The moulds were then kept at a constant room temperature of 20 ℃ for 24h, before added to the curing baths for 7, 14 and 28-days. There were three specimens per test and all samples were checked for their acceptable slump value in accordance with AS 1012.3.1 [64].

2.4 Testing procedure

The compressive strength test was performed on 200 x 100mm cylindrical specimens in accordance with AS 1012.9 [65] with a load rating of 20MPa/ minute. The flexural strength properties were determined on the concrete beams by conducting a four-point bending test. The size of the specimens were 100 x 100 x 350mm with a load rating of 1 MPa/min in accordance with AS 1012.11 [66]. The tensile strength properties were determined via indirect tensile testing, also known as splitting tensile test. The concrete cylinders were 100 x 200mm with a load rating of 1.5MPa/min in accordance with AS 1012.10 [66]. The compressive, flexural, and tensile values were measured at 7, 14 and 28-day intervals, with an average recorded of three samples for each mix design. All mechanical tests were conducted on the Matest C088-11N Servo-Plus evolution testing machine and Cyber-Plus evolution data acquisition system. The error bars of the recorded values represent the standard deviation on either side of the average. The microstructure of the samples was observed using a scanning electron microscopy (SEM) and an energy dispersive x-ray spectroscopy (EDS). These microstructure observations were conducted on the Phenom XL G2 Desktop SEM, samples were prepared using a diamond cutting saw to a height of 2-4mm and 4-6mm in diameter. The EDS analysis determined the chemical composition of the various mix designs.

3.0 Results and discussion

3.1 Microstructure

The microstructure of the reinforced composites was investigated for each mix design. There was an effective rate of fibre dispersion within the specimens and the mixing method adopted proved to be successful when dispersing the fibre materials within the concrete composites. Figure 2 illustrates the raw and modified fibre content. As can be observed, the fibre content various dramatically in size from approximately 10- 36μm. Although the fibre size is not uniform, it does allow the rate of fibre dispersion to increase. This allows the fibre to enter pockets and voids within the microstructure during the formation and agglomeration of the composite materials. The variation of size with KFs is shown in Figure 2 (a). This is because of the production and procurement of cellulose fibres for manufacturing cardboard products. The raw cellulose fibres are subjected to a complex chemical treatment to produce wood pulp. A caustic soda and sodium sulphide are often used as a liquor to then cook the wood pulp and release the bonding of the fibres. This process removes the lignin attached to the fibres to increase random fibre dispersion and size [30].

The composite samples when substituted with fibre and MK exhibited a drop in pH level. This was shown with pH levels of 11, 12 and 12 for samples SFKF55, SFKF and KF, respectively. Although this is not a significant reduction when compared to pH level of 14 for the control, it does demonstrate the reduction of alkalinity within the matrix environment. This reduction is shown to minimise the cement products attachment to the fibre cell walls and reduce fibre petrification as shown in Figure 3. It is important to note that the attachment between the SF and composite matrix is critical to establish an anchorage point for the SFKFs. This anchorage point is crucial for the bearing capacity of the fibre to withstand an increase of axial loading on the composite. The interfacial bond of the material is more critical than the mechanical properties of the individual fibre material [56]. SF creates a consumption of calcium hydroxide at later stages which increases the longevity of the fibre. During this process, C-S-H nucleation occurs which provides strength to the cement matrix.

Figure 2 (b) shows SF particles have attached themselves to the fibre walls sufficiently before integration within the composite material. This is further seen in Figure 4 that contains the EDS report of the raw KFs and SFKFs. The higher the percentage of SF on the fibre walls will reduce the alkaline zone around the fibre when applied in the OPC composite mix [54]. An additional benefit to modify the fibre with SF is to create an increase of surface area on the fibre. Although this enhancement may be minimal, it is effective when dispersing the fibre in a greater area [67]. The load transfer rate on the fibre is increased when subjected to axial loading because of the surface modification.

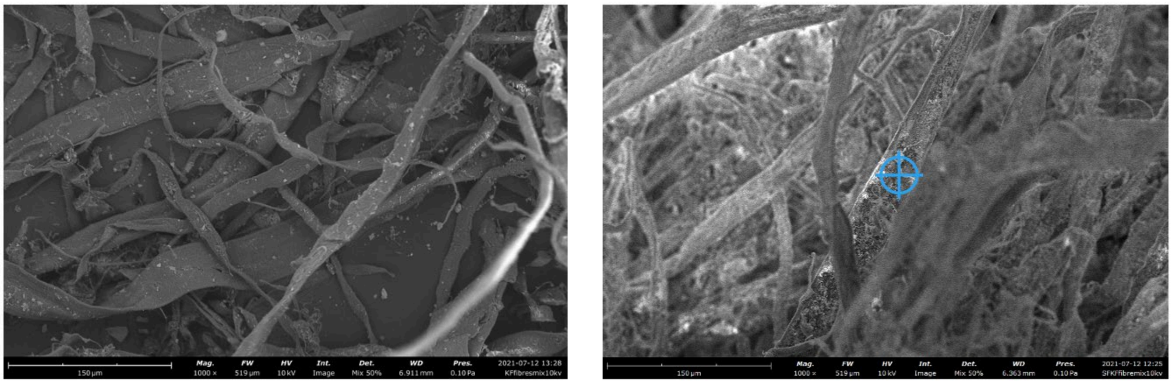
The SFKF55 interfacial properties between the fibre and composite matrix are shown in Figure 3. The samples in the SEM images are segments of the composite material. The Figure illustrates minimal precipitation of SF and cement products on the fibre, highlighting the reduction of alkaline attack on the fibre walls. Figure 5 illustrates advanced petrification on the non-modified fibre walls. This image depicts severe attachment of hydrated cement products which causes the fibre to become weak and brittle. Figure 3 demonstrates the matrix of the composite to be dense and rough in texture. This suggests improved bonding of fibres and lower moisture transfer rates. The minimisation of moisture transfer rates can be linked to the reduction of the pore microstructure of the specimens. Similar observations were reported by Booya et al. [24]. During the early stages of hydration, the saturation of gel pore water intensifies as C-S-H growth occurs. This changes the result of the capillary pores located near the KFs. The capillary pores decrease due to the hydrophilic nature of KFs, leaving an increase of consumed water within the matrix of the composite. This results with a decrease in porosity as compared to composites containing hydrophobic fibres [56].

The bonding ability of the SFKFs is graphically depicted with the increase of load transfer as shown in Figure 6 (b). There are two bonding mechanisms exhibited between the fibre and cement interfacial zone. Firstly, mechanical interlocking between the fibre and hydrated cement products creates an anchorage point on the fibre. Secondly, chemical bonding between covalent O-H bonds and weaker hydrogen bonds [56]. Fibre debonding has been the dominant cause when lower mechanical values are exhibited [24]. Figure 3 illustrates the embedded fibre, suggesting fibre pull out has not occurred. This demonstrates the increased pore microstructure surrounding the fibre within the composite material. This can be attributed to the SF modification undertaken prior to fibre composite application.

The influence of MK within the composite matrix can be seen in Figure 3. The fine MK particle size contains a higher surface area than cement. These particles reduce the pore size within the composite, this leads to less voids which also decreases permeability of the binary concrete blend. This further illustrates the increase of strength values for the SFKF55 composite, as hydration occurs MK is consuming $Ca(OH)_2$ during the early stages while SF consumes $Ca(OH)_2$ at later stages of ageing. This is in accordance with researchers that demonstrate the integration of SCMs transforming large pores into smaller pores. This reduces the permeability of concrete specimens. Booya, et al. [24] demonstrates SCM composites containing NFs exhibit lower absorptivity index rate when using SF and MK. Their research reported lower levels of MK integration were sufficient to enhance durability properties when compared to other SCMs such as GBFS and FA.

A reduction in permeability is primarily linked to the hygroscopic nature of cellulose fibres. NFs absorb moisture and once the completion of hydration has occurred, the moisture exits the composite material leaving voids and pockets surrounding the fibres. Due to this differential drying occurrence between the fibre and the matrix, the fibre-cement bond is often compromised. Claramunt et al. [68] described a process called ‘hornification’ to counteract this factor occurring. The researchers demonstrated that with sufficient pre-treatment of fibre material, NFs can show minimal moisture retention even when applied in a high moisture environment. This research attempted to the reduce the hydrophilic action of KFs via the removal of moisture from the fibre once SF was integrated on the fibre walls. With this phenomenon, the fibre had previously encountered two cycles of moisture retention and moisture release, firstly via the production of cardboard products then secondly to produce fibres for this experimental research. Other researchers [56] integrated nano-silica-fume (NSF) to combat the action of water retention with KFs. Their research reported a reduction of porosity and an increase of fibre-cement bonding with the interfacial zone of the composite material. As can be seen in Figure 3, the fibre is sufficiently embedded within the matrix.

There was sufficient agglomeration of MK and SF fibres within the mix design. This was shown in an area mapping of the composite within the EDS report. The results of the mapping are shown in Table 1. The mapping displayed traces of aluminium that can be accredited for the integration of MK. Silicon can attributed to the SF while the dominant element is calcium that is primarily linked to cement. This mapping further suggests that SF once integrated in a high moisture environment may break away partially from the fibres. This is seen in Figure 3, illustrating the composition of the fibre wall within the SFKF55 matrix. The fibre walls have traces of calcium and silicon however, the image displays primarily raw carbon of the cellulose matter. Although SF may attach itself adequately in a low moisture environment, once moisture is presented, the material appears to separate partially from the fibre walls.

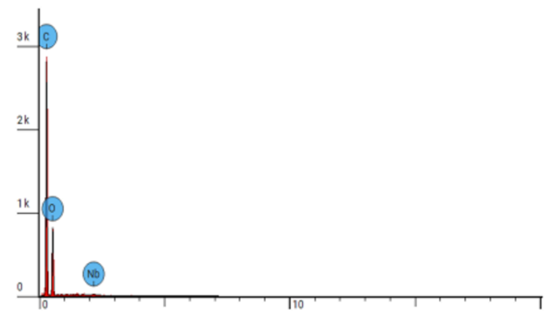


(a) Raw kraft fibres (b) Silica fume kraft fibres

Figure 2 Recycled kraft fibres modified and non-modified

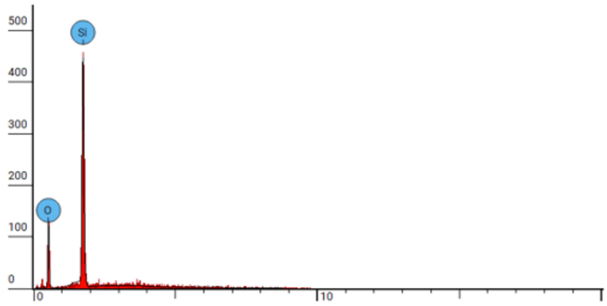
Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.
6	C	Carbon	33.241	23.500
8	O	Oxygen	53.301	50.200
13	Al	Aluminum	0.630	1.000
14	Si	Silicon	7.923	13.100
20	Ca	Calcium	4.705	11.100
41	Nb	Niobium	0.201	1.100

Figure 3 SFKF55 fibre and matrix analysis



Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.
6	C	Carbon	70.551	63.200
8	O	Oxygen	29.160	34.800
41	Nb	Niobium	0.289	2.000

(a) Kraft fibre



Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.
8	O	Oxygen	36.294	24.500
14	Si	Silicon	63.706	75.500

(b) Silica fume kraft fibre

Figure 4 EDS report of raw KF and SFKF

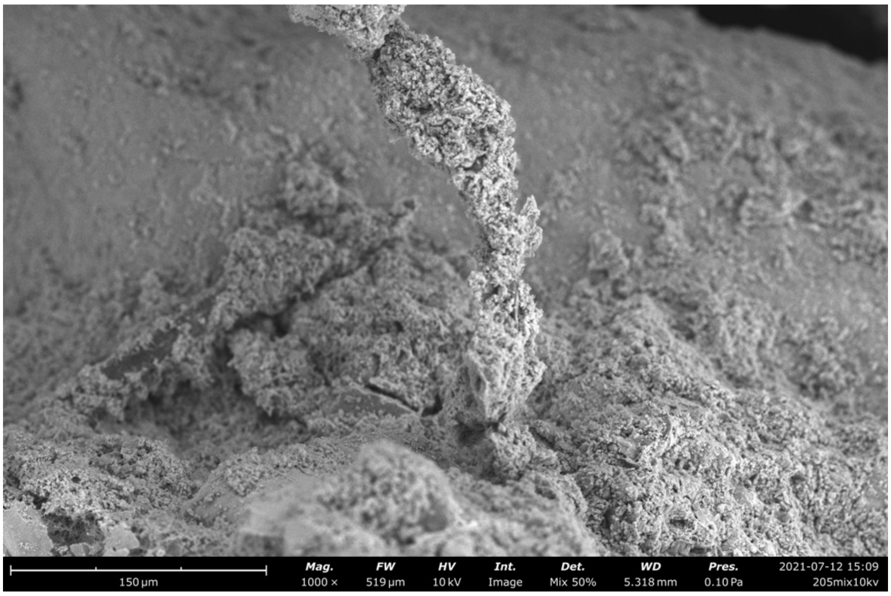


Figure 5 Total petrification of KF walls

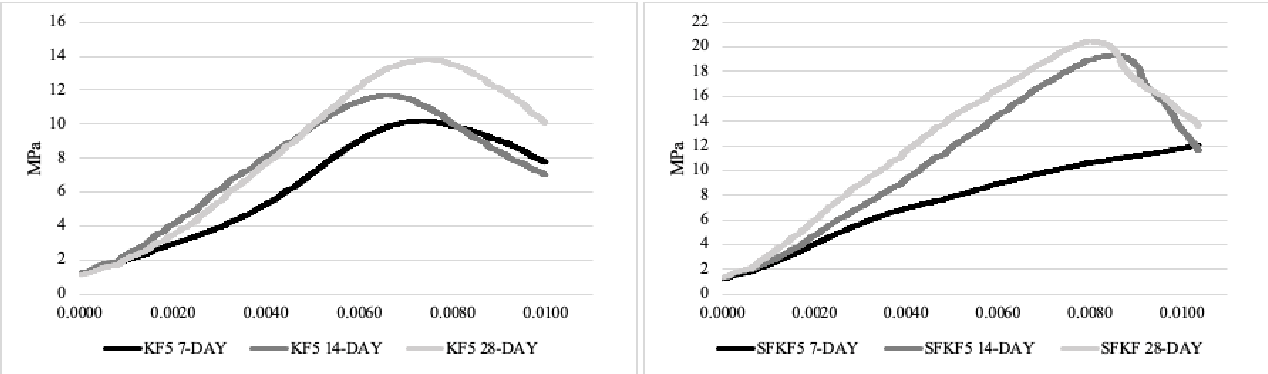
3.2 Compressive strength

The variation of compressive strength for concretes with various fibre types and sample composition are shown in Figure 7. The coefficient variation of the compressive strength was between 1- 2 MPa. The standard deviation is shown via the error bars on Figure *7*. The compressive strength of all samples decreases with fibre integration. The inclusion of fibre content in a cement matrix reduces the density and increases voids of composite specimens [24, 63]. The compressive strength values of plain concrete (control) measured at 7-, 14- and 28-day intervals were 17, 17 and 25MPa, respectively. Although the control sample contained the highest value on the 28-day measurement, SFKF5 concrete contained a higher value at the 14-day measurement. SFKF5 concrete strength was 12, 20 and 20MPa at 7-, 14- and 28-day respectively. The SiO_2 content that attached to the fibre walls has consumed $Ca(OH)_2$ at the later stage. This is shown with a significant increase of strength when compared to the values at the 7-day measurement. The values for KFs without modification are shown with a compressive strength of 10, 11 and 13MPa at 7-, 14- and 28-day, respectively. These values are significantly lower due to the attachment of hydrated cement products on the fibre walls. This is shown in Figure 3 where mineralisation has formed on the fibre. This process weakens the fibre and causes embrittlement to the fibre walls [39].

SFKF55 samples exhibited a strength increase of 11, 17 and 18MPa, at 7-, 14- and 28-day, respectively. The consumption of $Ca(OH)_2$ in early and later stages by MK and SF respectively, has reduced the attachment of cement products on the fibre wall and created a stable environment for the strength of the fibre concrete to increase with time. Although there is no rapid increase of strength properties, the fibres can maintain their strength and durability characteristics within the composite design. The integration of modified and non-modified KFs has reduced the overall compressive strength at the 28-day measurement. This is primarily due to the hydrophilic nature of the KFs which is under duress by the attachment of cement products. KF composites at 7- and 14-days contained the lowest strength which is a 70- 58% reduction respectively when compared to the control. Although this is primarily attributed to the attachment of cement products on the fibre walls, researchers have contributed lower mechanical strength due to fibre clumping within composite designs [69]. When the fibre composites are subjected to axial loading, there is a load transfer occurring within the microstructure between the fibres and the composite matrix. As the load increases, there is an increase of friction imposed on the fibre walls. If a significant amount of petrification has occurred on the fibre walls, the fibre will fail at a faster rate. This is shown in composite samples in Figure 6 (a), where the maximum fibre strain is significantly lower than the modified fibre strain in Figure 6 (b). Several researchers [30, 56] outlined the effect of crack bridging during the fracture process of fibre reinforced concrete and mortar samples. Crack bridging is when fibres will span in the voids between two cracks.

Crack bridging induced by fibres can improve the resistance size of crack openings. The formation of microcracks can be minimised with fibres, while mitigating the transference of those microcracks to larger crack propagation. Figure 6 (b) graphically depicts this with the rapid decline of strength post fibre rupture. The fibres endured the maximum axial loading until failure occurred. Whereas raw KFs contained a lower strength yield with a reduction of formation of crack bridging as shown in Figure 6 (a). The rounder curve of the gradient in Figure 6 (a) suggests a slow fibre pull out failure mechanism. The raw KF composite also contains a better residual strain after yielding. Figure 6 (b) illustrates SFKF composites have an increased bearing capacity, the steep curve after failure suggests a combination of fibre snapping and fibre pull out has occurred. This is further shown with a sudden reduction of residual strain when maximum capacity is reached. Figure 6 (a) demonstrates this factor by having a lower energy absorption rate which is shown in the area below the curve. The other key factor that attributed to the increase of compressive strength of modified fibres was the increase of density. The ultrafine SF particles that attached to the fibre cell wall has protected the fibre from high alkalinity but also increased the density of the fibre microstructure [54]. This is also in accordance with researchers reporting a 25% compressive strength decrease when fibres were not modified [70]. The increase of strength can be accredited toward the improvement of fibre bonding within the material composition. This is seen in Figure 4 (b) that illustrate the precipitation of SF primarily on the fibre walls. SF is effective when integrating within a cement environment because of the fine particles that act as a filler within the matrix. The particles reduce the porosity, forming increased levels of C-S-H that decrease the alkaline of the cement [46].

Materials with a higher density often have increased compressive strength. Khedari et al. [69] reported that the reduction in compressive strength can be attributed to the lower density of the properties of NFs. The properties are primarily concerned with the water absorption rate which can lead to an increase of voids and pockets within the composite matrix. When there is an increase of voids in the material, there is a decrease of material density. Therefore, as illustrated in Figure 7, the reduction of strength with fibre integration is to be expected. Another critical factor is the ratio of materials used within the mix design. Booya et al. [67] reported an increased compressive strength of 19.1- 45.6% when reducing the water-cement ratio from 0.5 to 0.35 in fibre reinforced concrete specimens. As previously discussed, the water content remained the same for all samples due to the minimal integration of fibre content.



(a) KF5 Compressive strength vs Strain (b) SFKF5 Compressive Strength vs Strain

Figure 6 KF5 & SFKF5 Compressive strength vs strain

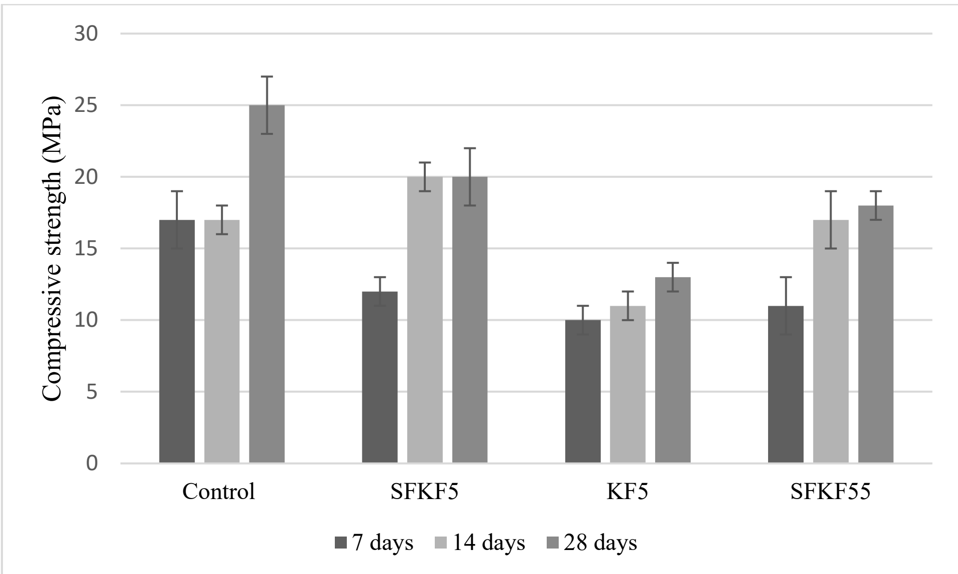


Figure 7 Variation of compressive strength

3.3 Tensile strength

Figure 8 graphically depicts the variation of tensile strength. The coefficient of variation of the tensile strength was between 1- 2MPa. The standard deviation is shown via the error bars in Figure 8. The development of fibre composition within a modified cementitious matrix is a key factor toward the overall tensile strength bearing capacity. As discussed with the crack bridging effect, an increased level of microcracks form due to fibre pull-out or fibre snapping. Consequently, the axial loading is then redistributed to other fibres. This results with an increase of load bearing capacity. A similar trend can be found with the indirect tensile strength results as seen in the compressive strength behaviour. This behaviour is graphically represented in Figure 8. However, the maximum strength values were shown with the composite design SFKF55. The values measured at 7-, 14- and 28-day intervals were 7, 10 and 11MPa, respectively. Although the results were similar to the control, there remained a linear incline that was seen with the compressive strength. The control samples reached 8MPa at the 7-day interval. This was also shown with the SFKF composite design. However, at the 14- and 28-day measurement, the strength remained the same at 10MPa. This was quite similar to SFKF, that exhibited a strength value of 9MPa at both 14-day and 28-day measurement. Research conducted by Toledo et al. [54] shows the immersion of NFs with SF creates a low alkalinity zone around the fibre, reducing the alkaline attack and mineralisation. Researchers agree that the non-cementitious nature of cardboard fibres can reduce the tensile strength within concrete and mortar samples [71]. However, this is specifically in reference to non-modified fibre and matrix designs. Further evidence that KFs require enhancement is shown with the tensile results of the KF mix samples. KF composites contained the lowest tensile strength, which was to be expected due to the embrittlement of the fibre within the high alkaline environment. It is interesting to note that the KF composite specimens although displayed lower strength than the other mix designs, the strength increased with curing time. KF composites measured at 7-, 14- and 28-day showed an increase with 4, 6 and 7MPa, respectively. This shows that KFs that are not modified reduce the process of continuous hydration within the concrete samples. This can be due to moisture retention on the fibre walls. Moreover, SFKF55 allowed continuous hydration to occur, shown with a strength increase above the KF composites at the 7-day measurement, then a gradual incline between the 14- and 28-day interval. This demonstrates the effectiveness of MK as a binary blend with OPC within concrete and mortar mix designs. MK mortar produces an increase of heat in early stages when compared to 100% OPC. This reaction consumes $Ca(OH)_2$, which protects the fibres while increasing C-S-H gel [72]. Researchers have agreed that MK composites exhibit similar strength to the control, however, the substitution ratio cannot exceed 30% [39].

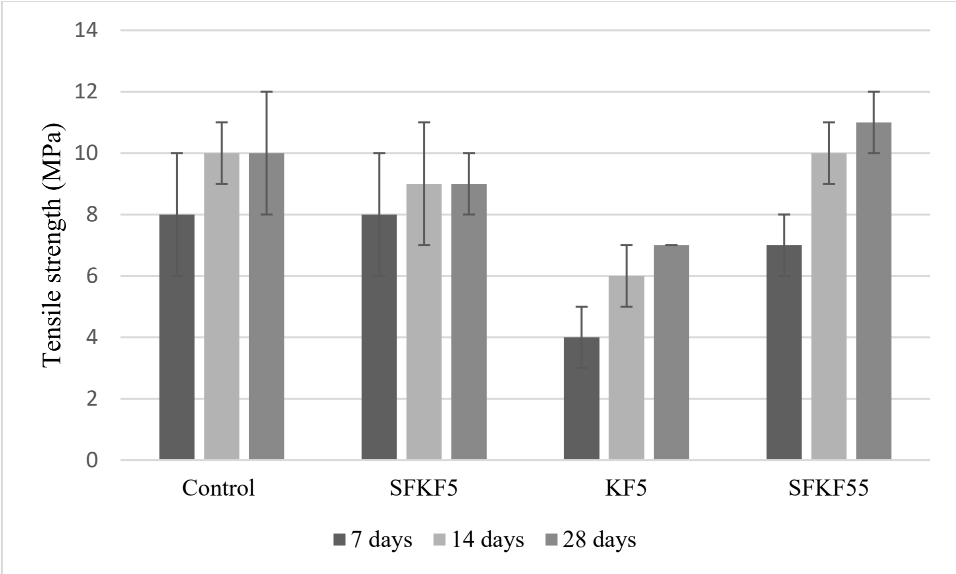


Figure 8 Variation of tensile strength

3.4 Flexural strength

Figure 9 shows the average maximum flexural strength, also known as the modulus of rupture (MOR). The coefficient variation of the flexural strength was between 0.2- 0.1, illustrating the data points are close to the mean. The standard deviation is shown in the error bars in Figure 9 which demonstrates the reliability of the recorded results. All samples subjected to flexural testing with fibre integration contained lower strength properties. This suggested fibre composite specimens withheld the 'balling effect' in flexural beams [30]. The balling effect refers to fibres clamping together causing weak points inside the composite. Figure 3 illustrates the lack of SF and cement products on the fibre wall. This can also lead to a lack of composite strength, as fibres should be absorbed completely within the composite. As the fibre content increases, there is a lack of hydrated cement products to be dispersed among all surface areas. This leads to a disruption of agglomeration of composite materials which ultimately leads to a weaker matrix.

SFKF5 and KF5 composites contained an increase whereas the control and SFKF55 exhibited the same flexural strength for each composite design at both 7- and 14-day intervals. The control measured 2.4, 2.4 and 2.6MPa at 7-, 14- and 28-day interval measurements, see Figure 9. The indirect tensile and compressive strength demonstrated a reduction in strength when raw KF was used, however, KF composite flexural results showed increased strength when compared to all other composite designs. The reduction in flexural strength for SFKF and SFKF55 is most likely due to factors such as a nonuniform dispersion and a weakening response of the binary matrix [63]. Researchers agree that substituting cement with non-cementitious materials within a composite design will reduce the flexural strength of the material [30]. The flexural durability of the fibre reinforced composites can also be shown via the post-cracking behaviour. During the acceleration towards maximum load, the development of micro cracks can be prevented via the agglomeration of fibres caused by the bridging mechanism. This mechanism prevails until the density of micro cracks achieves maximum saturation and the composite cannot withstand additional implied stress [73]. As shown in Figure 2 (b) the SFKFs are drawn together as a response known as the Van der Waals force [74]. The intermolecular attraction of KFs is increased when SF ultrafine particles are attached to the raw KFs. This attraction intensifies when water is introduced into the mix forming a stronger force of connection [74]. The raw KF composites have exhibited the formation of crack bridging to uphold higher strength levels. This is shown with the increase of strength at each interval measurement.

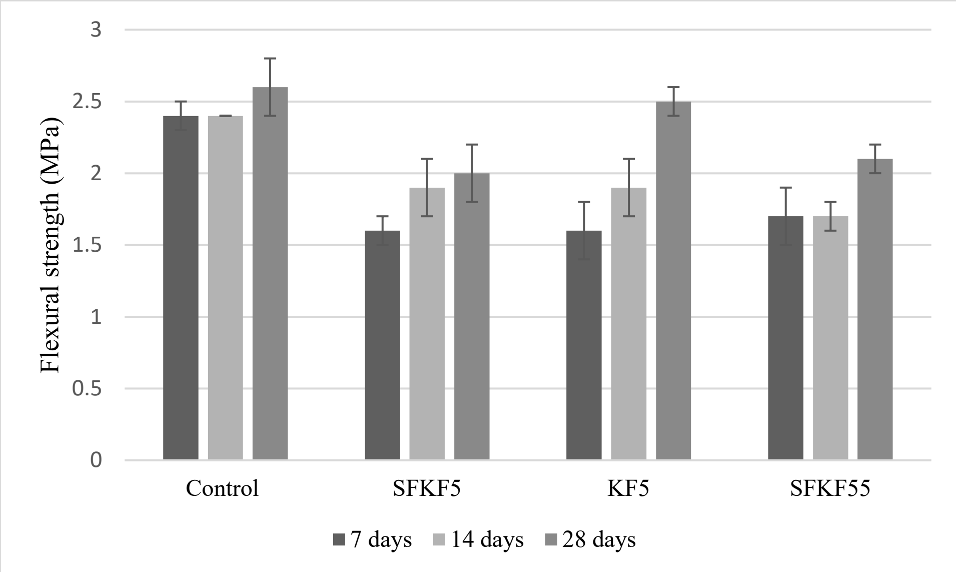


Figure 9 Variation of flexural strength

4.0 Conclusions and future research

This experimental study was conducted to evaluate the effect of waste cardboard with fibre and matrix modifications on the compressive, tensile, and flexural strength properties. The application of SF lowered the alkaline zone around the fibre to prevent attachment of hydrated cement products and mineralisation on KFs. The mechanical analysis of concrete samples containing raw KFs, modified KFs and matrix modified specimens demonstrated that waste cardboard fibres can be adequately integrated within concrete and mortar materials. The experimental procedure remained consistent when applying the different materials. However, the mechanical results demonstrated strength variations per mix design which is graphically represented via error bars. This variation is due to the batching process. The final agglomeration of all materials remained consistent, however; fibre clumping, and fibre dispersion were two factors that were irregular to maintain during the batching process. KFs are a non-homogeneous material within the cementitious matrix and can be inconsistent when compared to concrete and mortar materials. However, the workability of concrete was not compromised when fibre integration occurred, and the matrix bonding of samples was successful. Future research can be directed toward varying the percentage of KFs and the matrix modifier. Further investigations are required on the durability characteristics of the KF composites. The most important outcomes of this research are summarised as follows.

- SFKF composites had a 20% compressive strength reduction at the 28-day measurement, whereas KF composites withheld a 48% reduction. This demonstrates fibre modification using SF can enhance fibre strength within a cementitious matrix.
- Waste cardboard can be utilised further in concrete and mortar materials when being applied to lower concrete strength requirements.
- The integration of waste KFs can reduce landfill size and reserve virgin resource extraction.
- The investigation of the microstructure of the composites illustrated areas of fibre containing no SF or hydration products. This can increase the porosity of the composite leading to a decline in durability characteristics.
- Raw KFs contain a better modulus of elasticity and are more flexible than modified KF. This shows SF can increase the brittleness of the fibre when under flexural strain.
- This experimental study contained dry fibrous KFs. Further investigations are required of KF pulp.
- 5% KF integration exhibited satisfactory strength results for non-structural strength concrete.

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