The mechanical and microstructural performance of waste textile and cardboard materials in concrete

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The mechanical and microstructural performance of waste textile and cardboard materials in concrete

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Abstract

Waste fiber reinforced concrete is gaining recognition as a high-performance construction material, offering notable load-bearing capacity, corrosion resistance, and enhanced durability features. As the building and construction industry focuses on sustainable practices, fibers derived from waste materials create an opportunity to be utilized further in composite designs. This study explores the tensile, compressive, and flexural behaviors of cardboard fibers (kraft fibers) and textile polyester fibers in concrete materials. The composite microstructure is also investigated using a scanning electron microscope (SEM) to measure the bonding performance of the fibers within the cementitious matrix. Four mix designs were created using 2.5% textile fibers as a reinforcement agent and 5% silica fume modified kraft fibers (SFKFs) as a partial cement replacement. The combination of fibers achieved 44 MPa compressive strength, equaling the control. Tensile strength was enhanced by 5% when using the combination of the two fibers, achieving 3.58 MPa in comparison to 3.41 MPa. However, flexural strength was reduced among all fibrous concrete materials. SEM images distinguished the natural and synthetic characteristics associated with the two fibers within the cementitious matrix. Namely, demonstrating the chemical bonding of SFKFs in comparison with the physical bonding properties of the textile fibers. This study serves as a valuable resource for future investigations and the broader adoption of binary waste fiber composite designs in cementitious composite applications.

KEYWORDS

cardboard, composites, concrete, kraft fibers, mechanical, textile fibers, waste

1 | INTRODUCTION AND RESEARCH SIGNIFICANCE

The building and construction industry is experiencing continuous development, driven by constant innovations and advancements in technologies. A crucial area of these advancements is the use of novel materials to enhance the sustainability of common construction methods. The integration of waste materials and additives in cement manufacturing is one strategy aimed at reducing the damaging environmental impact of the industry. Ordinary Portland Cement (OPC) production is known to contribute 5%–8% annually of total carbon dioxide (CO_2) emissions globally.[1] By incorporating waste materials and additives, researchers hope to reduce the amount of cement needed in concrete production, thereby reducing carbon emissions.[2–5] Integrating waste fiber materials, such as textile and cardboard waste in concrete can offer several benefits. Firstly, these fiber materials can enhance the performance of concrete by reducing crack propagation, increasing tensile, and toughness capacity.[6–8] This is particularly valuable as concrete is known for its low tensile strength.[9] The incorporation of fibers can improve the overall durability and structural integrity of concrete. This is shown by researchers reducing crack propagation to mitigate degradation caused by induced moisture content.[10] Moreover, the use of waste fibrous materials in concrete contributes to sustainable practices within the building and construction industry. This can be shown by reducing the overall quantity of steel reinforcement, thereby the negative impacts associated with steel extraction and production can also be minimized.[11] This assists in the conservation of natural resources and can reduce carbon emissions.

Incorporating waste materials in concrete can partly address the issue of waste accumulation in landfill areas. For example, diverting textile and cardboard waste from landfill and utilizing them in concrete and mortar materials, can reduce the amount of waste sent for disposal, leading to a more sustainable waste management approach. It is worth noting that the utilization of various fiber types such as steel, plastics, textiles, and glass in cementitious composites has been observed globally, indicating the potential of waste fiber materials in concrete applications.[12–15] However, research studies have focused on utilizing one fibrous material per mix design. Therefore, research is required to demonstrate the use of a multiple fibers within a composite design to address the issues of both cement and steel requirements. Additionally, there are limitations to consider with waste materials, such as the availability and cost-related concerns of waste products. Ensuring a consistent and sufficient supply of textile and cardboard waste may require effective waste management systems and collaborations between industries and waste management authorities.

Annually, the textile industry consumes around 98 million tons of non-renewable resources, including oil, raw materials for fertilizers, and treatment chemicals.[16] This results in a significant carbon footprint, with the textile industry accounting for 1.2 billion tons of CO_2 emissions, equivalent to 8% of the global total.[17] Globally, the production of garments reaches a staggering 100 billion units per year, with a substantial portion of 92 million tons ending up in landfills.[18] This waste issue is primarily driven by consumers' economic feasibility in purchasing new clothing. Moreover, mass production of textile materials has resulted with reduced material costs due to over-supply. This additionally creates an abundance mentality with consumers and ultimately creates more waste textiles. The recycling of textile products requires substantial energy and economic resources, leading to significant challenges in repurposing. Consequently, a large volume of textiles ends up in landfills, necessitating the development of alternative recycling solutions. The United States Environmental Protection Agency (EPA) estimates that approximately 26 billion pounds of textiles are disposed of in landfills each year.[19] Similarly, Australia discards approximately 501 million kilograms of textiles annually.[20] As the global population is projected to reach 8.5 billion by 2030, the accumulation of textile waste will continue to escalate.[21] This population growth amplifies waste generation across all sectors, particularly in the case of cardboard materials. Textile materials are becoming a prominent reinforcing method in cementitious composite materials.[22] Islam et al.,[23] have integrated carbon fiber textile grids and short textile fibers within concrete materials to improve the mechanical behavior. Their findings demonstrated that shorter fibers improved the plastic behavior of concrete. Moreover, findings from Islam et al.,[23] highlighted the use of a double layered carbon textile grid improved the flexural load capacity by 2% and the tensile capacity by 30%. Other research focused on the binding properties of textile materials in concrete.[24] Preinstorfer et al.,[24] findings demonstrated that the textile fiber type is critical to enhance bonding when the composite is under applied load. This is shown with the geometric properties of the fiber strands. A tricot-binding pattern was beneficial in the warp direction of plain textiles as it creates a rough surface area. This enables an interlocking mechanism surrounding the textiles in the concrete and ultimately reduces crack propagation. However, the previous research investigates longer fiber lengths which can be difficult to procure from recycled sources. However, Ibrahim et al.,[25] investigated the use of both carbon textile grids and short carbon fibers in concrete. The findings demonstrated that short carbon fibers contributed to more flexural strength in a concrete slab than they do in a hybrid textile grid and short fiber systems. Moreover, Ibrahim et al.,[25] demonstrated that short carbon fibers can improve both the load-deflection and load-concrete strain behavior. This is primarily due to the random dispersion of fibers that reduce the number of cracks originating in the composite.

Another potential solution that has often been overlooked is the utilization of cardboard waste materials in concrete. However, challenges arise from its natural material origin. In 2021, Australia achieved a resource recovery rate of 61.2% for cardboard waste, recycling 55% and directing 6.2% toward energy recovery. Despite these efforts, a significant amount of 2.2 million tons (Mt) of cardboard waste still ended in landfill.[26] This figure is noteworthy, considering that one ton of cardboard waste occupies a volumetric size of 1.6 m^3. Cardboard is extensively used across various industries, and the demand for cardboard packaging for households has risen by 40% since the onset of the COVID-19 pandemic.[27] Therefore, to sustain future advancements in composite designs, it is crucial to explore customized approaches that maximize the utilization of these materials. Moreover, comprehending the mechanical behavior of textile and cardboard waste in concrete is essential for promoting their use as alternative reinforcement and cement substitute methods in composite designs. The integration of cardboard waste in concrete and cementitious materials has been explored in research.[28] The constituent material in cardboard is kraft fibers (KFs), which is a natural material derived from plants and trees.[29] However, the successful integration of this material in cementitious composites requires additional fiber and matrix modifications.[30] A key challenge is that the cellulose chains of KFs degrade significantly when exposed to high alkaline environments.[31] In an experimental investigation by Khorami et al.,[32] waste cardboard was studied by integrating 1%–14% KFs within fiber cement boards. The research findings revealed that the flexural strength improved by 250% when 8% KF was combined with 10% limestone powder and 3% nano-silica fume. These additional additives reduced fiber wall degradation by reducing the amount of OPC used. Another experimental study conducted by Booya et al.,[33] focused on the durability of KF integration in concrete. The results demonstrated that the incorporation of 2% mechanically and chemically treated fibers can enhance the durability properties of concrete composites. Other research efforts have examined the thermal performance, microstructural characteristics, surface fatigue, and processing effects of KFs when integrated into cementitious composites.[34–37] However, these studies primarily aimed at achieving mechanical objectives when using the material as a reinforcement agent. Other research has been conducted utilizing silica fume (SF) as a fiber modification technique to reduce the amount of OPC required in concrete.[38] The findings demonstrated the potential to supplement 5% OPC with silica fume modified KFs (SFKF)s. Moreover, the mechanical investigations demonstrated a 20%, 10%, and 26% reduction in compressive, tensile, and flexural strength. However, the use of the material was primarily focused on reducing the OPC requirement, rather than the reduction of reinforcement materials. Further studies have focused on the utilization of waste cardboard fibers to reduce economic and environmental concerns.[39] The findings demonstrated a reduction in GHG emissions when integrating waste materials as a raw material in concrete.

This study will focus on the use of two waste fiber materials to investigate two alternative solutions. Firstly, textile materials will be utilized to act as a reinforcing agent in concrete and secondly, KFs will be integrated as a partial cement substitute. The novelty of this research is the use of two fibrous materials that will have two different purposes. Moreover, the use of both textile and KFs in concrete has been seldom considered. To encourage the incorporation of textile and cardboard waste fibers in concrete, this study will comprehensively analyze the mechanical and microstructure of the composite materials. The creation of the novel composites can assist to better understand the potential benefits and challenges associated with using these materials as a binary fiber blend in concrete and mortar materials.

2 | EXPERIMENTAL PROCEDURE AND METHODOLOGY

2.1 | Materials and preparation

Textile materials were sourced from pre-used high vis construction vests. The fibers derived from the vests were polyester materials. The vests were shredded and transformed into a fibrous material, ready for laboratory exploration. The primary materials used to reduce the OPC content in the mix designs are waste corrugated cardboard and metakaolin (MK). Waste cardboard was transformed into a fibrous material through the integration of SF, which acts as a fiber modification technique. The process begins by reducing the waste cardboard to a pulp material using water immersion and rotating mixing methods. SF slurry is then applied to the cardboard fibers, resulting in Silica Fume Kraft Fibers (SFKFs). SFKFs undergo a moisture removal process and are mixed in a rotating mixer, creating a fibrous material. The SF applied to the waste cardboard (KFs) adheres to the Australian Standard AS/NZS 3582.3[40] specification for silica fume used in cementitious materials. The MK, used as a partial substitute for cement, conforms to the ASTM C-618[41] Class N specification for natural and calcined pozzolans. OPC, conforming to AS/NZS 3972,[42] is included in the mix design as the primary component for pozzolanic reactivity. Table 1 details the various chemical components of SF, MK and OPC. The use of locally available (Melbourne, Australia) 20 mm Coarse and 0.6 mm fine aggregates, are used in accordance with AS/NZS 1141.6.2[43] and AS/NZS 1141.5,[44] respectively. Regular potable tap water was used in the preparation of the specimen designs.

Sample preparation is conducted using a mortar mixer following the guidelines of AS/NZS 1012.2.[45] The materials are dry mixed for 5 min. Subsequently, water is added and mixed for an additional 5 min to complete the

TABLE 1 Chemical composition of pozzolanic materials.

Chemical	Material component %		
	MK	SF	OPC
SiO_2	54–56	≥75 to <100	19–23
Al_2O_3	40–42		2.5–6
$Fe_2 O_3$	<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 to <1	
$CaSO_4.2H_2O$			3–8
$CaCO_3$			0–7.5
Fe_2O_3			0–6
SO_3			1.5–4.5

Abbreviations: MK, metakaolin; OPC, ordinary Portland cement; SF, silica fume.

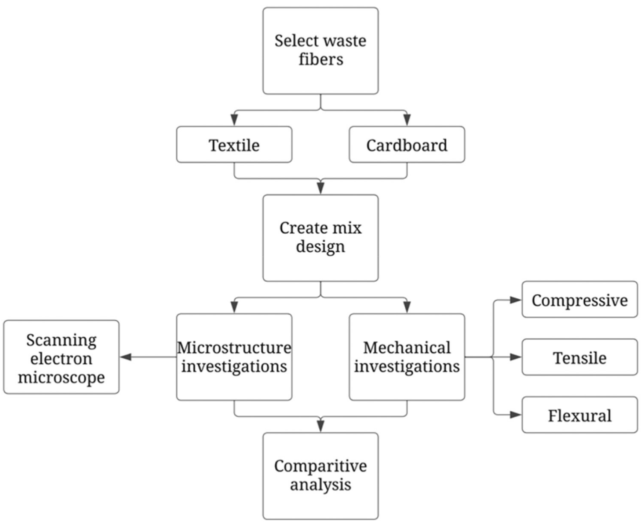


FIGURE 1 Research methodology.

sample preparation. Once ready, the concrete materials are added to the molds in three layers. Each layer is compressed 20 times using a steel rod before the subsequent layers are added. The molds are kept at a room temperature of approximately 20°C for 24 h before being placed in curing baths. Slump tests are performed following the procedures outlined in AS/NZS 1012.3.1.[46] As shown in Figure 1, the methodology framework consists of both mechanical and microstructure investigations.

2.2 | Mix designs

The desired compressive strength for all concrete specimens was 40 MPa. The experimental mechanical analysis included five different mix designs. The first design served as the control without any fiber integration. The second design incorporated 2.5% textile (T2.5) materials to act as reinforcement. The third design involved 5% SFKFs (SFKF5) to supplement 5% cement. The fourth mix design (MKT) combined 5% MK and 5% SFKFs to partially supplement cement with 2.5% textiles as reinforcement. Lastly, the fifth mix design combined 2.5% textiles as a reinforcement with 5% SFKFs to partially supplement cement (KFT).

The specific formulations of the mix designs can be found in Table 2. The density of the fiber materials needed to be adjusted based on the purpose of the materials. For example, to supplement cement with KFs, the weight of KFs needed to be adjusted based on the density of the cement. This is similar to the textile materials to act as a reinforcing agent based on the density of the concrete. The water content, as well as the ratios of fine and coarse aggregates, remained consistent with the control design. Regardless of fiber integration, the workability of the fiber concrete remained satisfactory during the mixing process.

TABLE 2 Mix design ratios (kg/m^3).

Mix design	Fiber	Cement	Metakaolin	Coarse aggregate	Fine aggregate	Water
Control		424		1241	587	195
T2.5	4.16	424		1241	587	195
SFKF5	3.3	402.8		1241	587	195
MKT	7.46	381.6	21.2	1241	587	195
KFT	7.46	402.8		1241	587	195

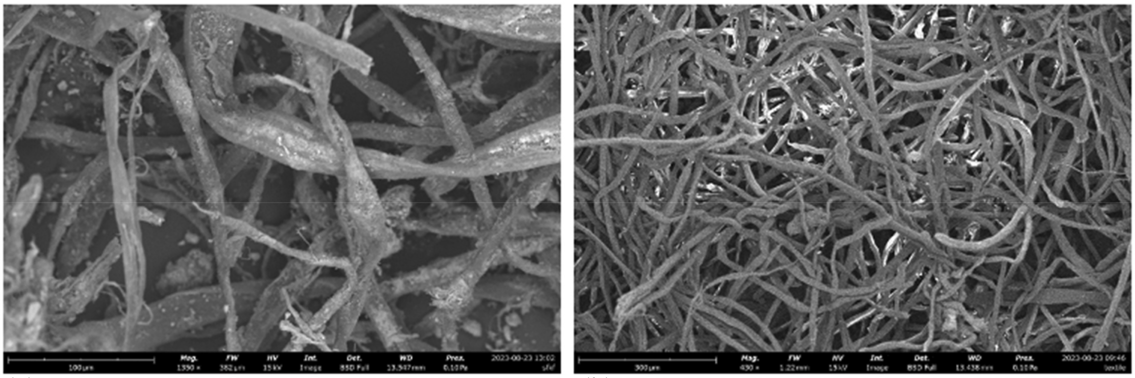

(a) SFKFs (b) Textile fibers

FIGURE 2 Fiber materials.

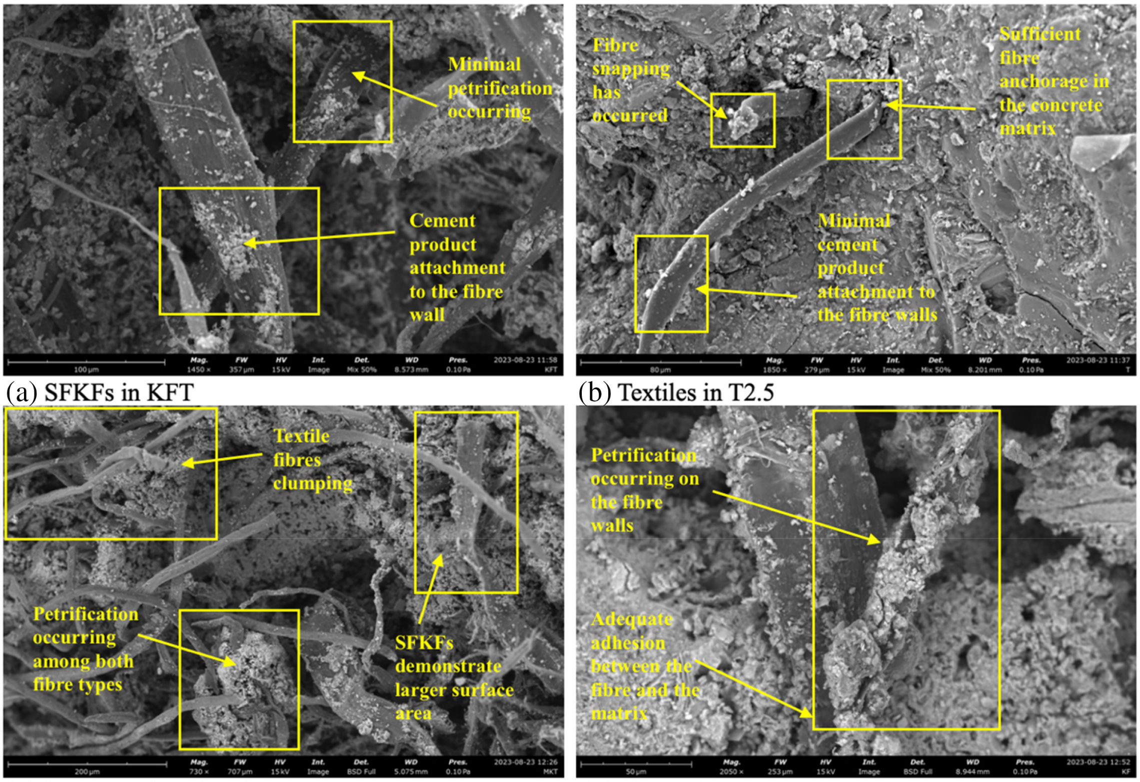
2.3 | Testing procedure

Following the concrete testing methods outlined in AS/NZS 1012.8.2,[47] both compressive and tensile tests were performed on cylindrical specimens measuring 100 × 200 mm. The compressive load rate was set at 20 MPa/min, as specified by AS 1012.9.[48] Indirect tensile testing was conducted with a load rate of 1.5 MPa/min, in accordance with AS 1012.10.[49] The flexural strength properties were determined on the concrete beams by conducting a four-point bending test. The size of the specimens was 100 × 100 × 350 mm with a load rating of 1 MPa/min in accordance with AS 1012.11.[50] For each specimen, three samples were measured at aging intervals of 24 h, 7, 14, and 28 days. The average values and standard deviation measurements were recorded. The mechanical tests were carried out using the Matest C088-11N Servo-Plus evolution testing machine and the Cyber-Plus evolution data acquisition system. To examine the microstructure of the samples, scanning electron microscope (SEM) and energy-dispersive X-ray spectroscopy (EDS) were employed. The microstructure observations were performed using the Phenom XL G2 Desktop SEM. To prepare the samples, a diamond cutting saw was used to create specimens with a height of 2–4 mm and a diameter of 4–6 mm.

3 | RESULTS AND DISCUSSION

3.1 | Microstructure

The microstructure of the composites was investigated for each mix design. Figure 2 illustrates the waste fibers used in the concrete materials. As shown in Figure 2a, SFKFs demonstrate a larger surface area compared to the textile fibers. The length of the SFKFs varies greatly between 10 and 36 μm. This is due to the process of acquiring and producing cellulose fibers use in the manufacturing of cardboard materials. Raw cellulose fibers undergo intricate chemical and thermal treatments to wood pulp. Caustic acid and sodium sulfate is employed to cook the wood pulp, breaking down the fiber bonds. Consequently, this method eliminates lignin from the fibers, enhancing both random fiber dispersion and size.[51] Moreover, SFKFs then demonstrate a rough surface area due to this process. SFKFs are susceptible for dimensional changes due to moisture absorption when applied in the composite materials. However, the rough surface area can aid toward the anchoring system within the concrete matrix. This anchorage point is critical to enable the fiber to endure elevated axial loads within the composite, thereby enhancing the total bearing capacity of the material.



(a) SFKFs in KFT (b) Textiles in T2.5

(c) SFKFs and textiles in MKT (d) SFKFs in SFKF5

FIGURE 3 SEM images of fibers in various mix designs. SEM, scanning electron microscope.

The synthetic production of the textile fibers as shown in Figure 2b, have a unified formation. Despite the recycling process of the textile materials, the fibers remain smooth and unhindered from the shredding process. The length of the textile fibers are between 7 and 12 μm. The smooth texture increases the effective dispersion rate during the mixing process, as the fibers are less likely to clump together. Moreover, this enables the fibers to penetrate voids and gaps within the microstructure during the formation and agglomeration of the concrete materials. Increasing the fibers presence among the matrix of the materials increases the ability of the fiber to act as a reinforcement agent during the application of mechanical stresses.

Figure 3 illustrates both fibers in the various concrete mix designs. As can be observed in Figure 3a, SFKFs have an attachment of cement products on the fiber walls. This attachment can reduce the durability and service life of the fiber. Moreover, various components such as calcium hydroxide ($Ca(OH)_2$) that have high alkalinity can weaken the fiber. The outer lumen of the natural fibers can degrade significantly rendering the fiber susceptible to fiber snapping. However, the integration of SF on the KFs appear to reduce the attachment of cement products along the entire fiber. SF consumes $Ca(OH)_2$ and creates additional calcium silicate hydrate (C–S–H) gels among the composite material. Moreover, the use of SF on the fibers creates additional durability benefits because the interfacial zone between the fiber and the matrix is improved with the creation of additional C–S–H gels. Figure 3b illustrates textile fibers within T2.5. As shown, the structural integrity of the textile fibers remains mostly unhindered from the attachment of cement products. The chemical composition of polyester fibers lacks chemical affinity within cementitious materials. Therefore, the use of polyester fibers in concrete materials are predominantly used for their physical attributes and cannot be relied upon for their chemical bonding in cementitious matrices. For this reason, polyester fibers are primarily used in composites so assist in the reduction of crack propagation and improve the overall mechanical performance. The lack of chemical affinity between the fibers and the matrix prevents the formation of strong bonds. However, as can be observed fiber snapping appears to have occurred to the textile fibers in the composite. This demonstrates a sufficient bond between both the fiber and the matrix which has allowed the fiber to absorb excessive stress until failure has occurred. This is critical to observe as to fiber pull-out typically occurs when using polyester fibers in cementitious composites.

Figure 3c illustrates the use of both fiber types in the MKT mix design. As shown, there significant crowding

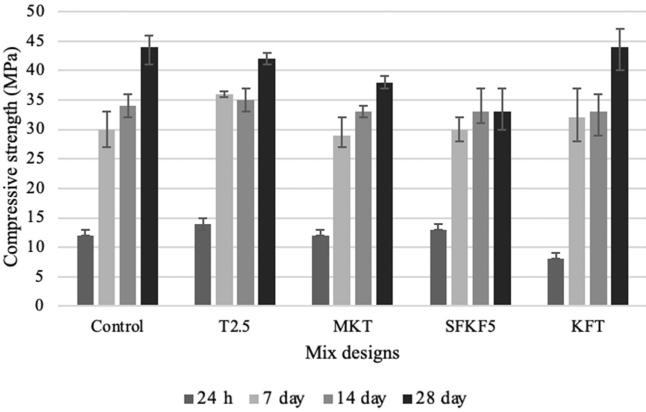


FIGURE 4 Compressive strength results.

among the dispersion of both fibers in this localized area. The textile fibers appear to have clumped together, with a similar occurrence among both fiber types in the composite. Similar observations can be seen among the various composites using textiles, with little to no degradation occurring. This image demonstrates the significantly larger surface area of SFKFs compared to textiles. The increased surface area can aid toward the mechanical function of the composite when a larger surface area is exposed to the axial forces. However, it appears there is a higher rate of dispersion with the textile fibers that has filled the various voids and gaps in the microstructure of the composite. A higher rate of dispersion allows the fibers to act as a reinforcement agent as there is a higher chance the fibers will receive the mechanical loading applied to the composite. It is important to note that the SFKFs are predominantly used as a partial cement replacement and therefore the higher rate of dispersion of textile fibers was to be expected. Figure 3d demonstrates petrification has occurred to the SFKFs. As can be observed, cement products have attached to the outer fiber. This occurrence can result in the fiber becoming brittle and reduce the elongation of the fiber when mechanical forces are applied. Although this is one demonstrated occurrence, it is important to note that other SFKFs in the same region do not contain similar patterns of petrification.

3.2 | Compressive strength

Figure 4 illustrates the variation in compressive strength among the different concrete samples with various fiber types and compositions. The standard deviation in concrete strength between the samples is shown via error bars. The control measured 12, 30, 34, and 44 MPa at 24 h, 7-, 14-, and 28-day intervals, respectively. The target compressive strength was 40 MPa. Samples T2.5, MKT and SFKF5 achieved a compressive strength of 42, 38, and 33 MPa, respectively. However, KFT equally reached a strength of 44 MPa at 28 days. KFT demonstrated a higher range in strength volatility in comparison with the control. This is shown with an increased range of upper and lower limits of the samples between 1 and 2 MPa. Although this amount is marginal, it does demonstrate the variables associated with fiber integration in concrete.

The smaller surface area of the shredded textile materials enabled the material to fill voids in the concrete matrix. This is shown when analyzing the strength differences between T2.5, SFKF5, and KFT. SFKF5 had the lowest value of compressive strength with 33 MPa at 28 days. However, T2.5 had the second highest compressive strength with 42 MPa at 28 days. Although the cement content varied, this demonstrates the ability of the fine fibrous textile materials to fill any voids by containing a high compressive strength. It is important to note that SFKF5 reduced the cement content by 5% with the integration of SFKFs as a partial substitute. However, when textile fibers are combined with KFs, there is a 11 MPa increase. As shown with the sample KFT. This further demonstrates that a key factor in high compressive strength correlates to the packing density of the concrete matrix. The early ages of T2.5 showed an increased compressive strength compared to all samples. For example, 24 h, 7- and 14-day intervals demonstrated 14, 36, and 35 MPa, respectively. However, the control had 12, 30, and 34 MPa within the same age range. As the concrete cures, the hydration process causes the cement particles to react with the water molecules, forming a crystalline structure known as C–S–H gel. This gel binds the various components of the concrete mix, increasing the strength and durability. Additionally, the formation of other compounds, such as $Ca(OH)_2$ and ettringite also contribute to the strength development.[52] This is shown with researchers utilizing basalt textile grids in concrete. Their findings revealed that a cementitious binder outperformed the geopolymer binder in terms of compressive and tensile strength.[53] Their results exhibited compressive and tensile strength increased by 25.56% and 10.6%, respectively. This study further exemplifies the chemical composition of the fiber is a critical element toward the mechanical effect of the composite material. When the fibers integrity is not hindered due to the chemical components of cement, it can increase the strength qualities.

The development of $Ca(OH)_2$ over time can contribute to the reduction in strength within cementitious fiber composites. This is shown with T2.5 and SFKF5 where the high strength levels are shown in early ages of the

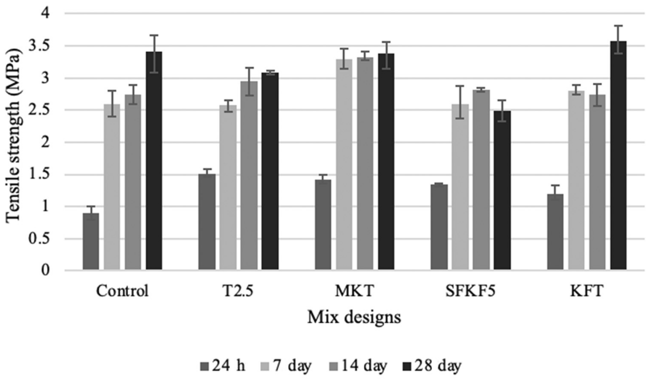


FIGURE 5 Tensile strength results.

concrete development but reduced at the final 28-day interval. $Ca(OH)_2$ has been shown to reduce the durability of fibers due to the degradation caused on the fiber walls.[54] Fibers can become weak and brittle due to the attachment of cement particles on the fiber wall, this is also known as petrification. When the surface area of the fibers are petrified, fiber snapping is more likely to occur due to the reduced flexibility of the crystalline materials. This is one phenomenon of mechanical failure of fibers in composite materials. However, the application of SF on the KF walls reduces the accumulation of $Ca(OH)_2$ on the fiber walls, thus reducing petrification. This is due to the high silicon dioxide (SiO_2) content of SF reacting with the $Ca(OH)_2$ to form additional C–S–H gels, consuming $Ca(OH)_2$. Moreover, the consumption of $Ca(OH)_2$ via the pozzolanic reaction of SF reduces the alkalinity within the concrete materials. This reduction of alkalinity additionally reduces the degradation on fibrous materials. This is highlighted by the mechanical strength variation of KFs used within concrete without SF fiber modification.[55] Haigh et al.,[55] demonstrated the addition of SF coating strengthened the compressive strength and enhanced the durability of the fibers despite the amount of KFs used. This was shown with 15% raw KFs exhibiting 10 MPa whilst 20% SF modified fibers demonstrated 11 MPa. A 5% fiber increase can be detrimental toward the compressive strength of composite materials however, as shown, the integration of SF reduced the negative mechanical effects often associated with high volume fiber concrete.

3.3 | Tensile strength

Figure 5 illustrates the variation in tensile strength among the different concrete samples with various fiber types and compositions. The standard deviation in concrete strength between the samples is shown via error bars. The tensile strength of the concrete increased with fiber integration. This is shown with KFT demonstrating 3.58 MPa at 28 days compared to the control which achieved 3.41 MPa at the same aged interval. However, MKT also achieved similar results with a total of 3.38 MPa at 28 days. It is important to note that MKT demonstrated the highest tensile strength results at 24 h, 7- and 14-day aged intervals. The chemical composition of MK within the concrete mix has shown to influence the tensile strength. This is via several factors such as the pozzolanic reactivity, microstructure features and the synergy between the fibers. MK contains amorphous silica and alumina which is highly reactive within cementitious materials. Its pozzolanic reactivity with $Ca(OH)_2$ forms additional C–S–H gels which can enhance the bonding between the fibers and the matrix.[56] Enhancing the fiber bonding capacity improves tensile strength by effectively transferring stress between the two materials, thus reducing the formation of microcracks.[57] Moreover, the addition of C–S–H gels contributes to a denser concrete matrix and reduces porosity. This creates a more compact and homogenous matrix, which provides improved support for the fibers against tensile forces.[58] Additionally, MK influences the microstructure via the reduction in the pore structure and ultimately improves particle packing. However, it is important to note that reducing 5% cement with MK does not eradicate the total development of $Ca(OH)_2$. For this reason, degradability can still occur on the fibers within the matrix as shown with the marginally reduced tensile strength of MKT at the 28-day aged interval. Alan Strauss Rambo et al.,[59] improved the tensile and bonding of sisal textile fibers in concrete via nano-silica treatment. It is important to note that the control demonstrated higher tensile strength however, the fiber modification technique was improved compared to raw fiber integration. This was further exhibited by the reduction in crack formation, which aided toward the increase of tensile strength.

SFKF5 achieved the lowest tensile strength among the samples with an 11% strength reduction occurring between 14- and 28-day intervals. This can be attributed to the degradation of the fiber within the matrix. There is a progressive development of degradation that occurs to natural fibers in cementitious materials when compared with their synthetic fiber counterparts. Natural fibers absorb moisture within the concrete matrix, this leads to dimensional changes and weakening of the fibers. This absorption and release of moisture can create a physical degradation, reduced strength, and loss of structural integrity. Moreover, natural fibers are more prevalent to alkali attacks in a cementitious matrix. Thus, weaking the fiber structure and subsequent degradation. However, it is important to note that there is a significant strength increase when SFKFs are paired with textile fibers. As discussed, the fine surface area of textile fibers has created a denser matrix by

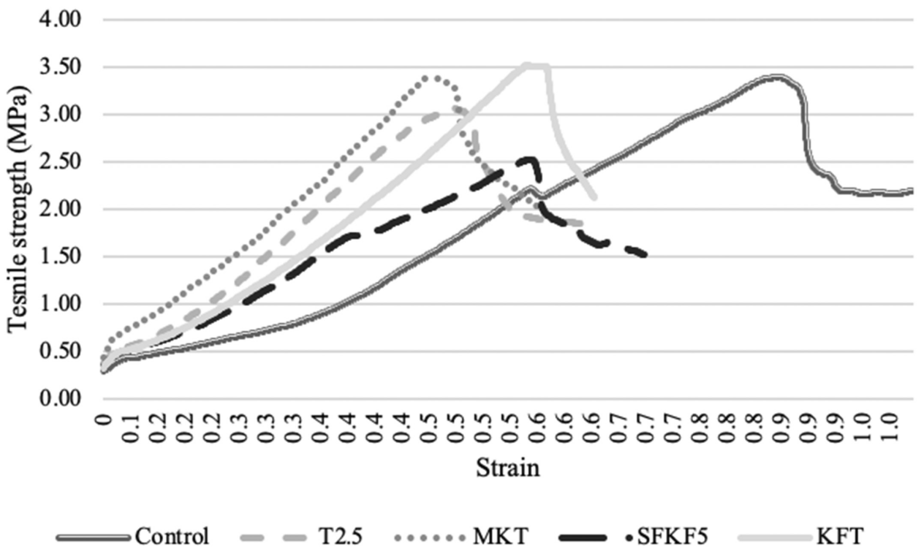


FIGURE 6 Tensile stress versus strain.

reducing the porosity of the composite. Li et al.,[60] utilized polyethylene (PE) fibers and carbon fiber textile grids in concrete. Their findings demonstrated that increasing the PE content and carbon fiber textiles can improve the properties of the tensile specimens after the initial cracking. This was shown with an increased tensile load capacity and hardening modulus of the samples. Additionally, short and dispersed fibers improved the bonding properties between the textiles and the matrix. In this study, when both fibers are integrated, the transference of applied load can alternate within the matrix between fiber types. This creates a stronger composite by minimizing the accumulation of forces upon one fiber type. The optimal amount of cement replacement in this mix design is 5%, as shown in KFT. However, this is only when the addition of textile fibers are integrated within the mix design. T2.5 demonstrated an incline of tensile strength at each aged interval. T2.5 achieved the highest tensile strength at 24 h but then showed the lowest strength improvement between 24 h- and 7-day aged interval. Although T2.5 maintained a high tensile strength across each aged interval, the fine surface area of the textile material did not allow the transference of significant load to occur between fibers.

Figure 6 graphically illustrates the tensile stress versus strain curve of the various mix designs. It is important to note the numerical values presented are from one of the three samples tested. The variation of maximum strength are shown via the peak curves. As demonstrated, KFT had a higher stress yield that the other composite materials. However, the control exhibited a much longer strain duration compared to the other mix designs. This is shown with the control achieving the maximum stress load later than the other composite samples. MKT exhibited the highest strength increase followed by the shortest strain duration. SFKF5 demonstrated the sharpest strength decline following the highest strength yield for that composite. The variation of curves indicates different tensile capacities of the materials. For example, a steeper decline can exhibit fiber snapping occurring in the composites matrix. Additionally, the longer incline of the tensile strain can demonstrate the sufficient bonding between the fiber and the matrix. Moreover, when load is applied to the composite, a load path is created throughout the matrix. When the fiber has sufficient bonding and strength in the composite, the fiber can withstand the load that is being applied. Therefore, when there is an increased strain capacity of the composite, there is a mechanical benefit from the fiber integration. Alternatively, the increased strain on the control shows the sufficient agglomeration of all constituent materials.

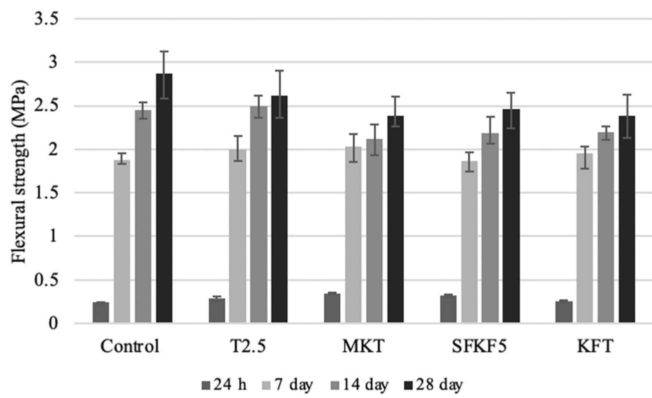


FIGURE 7 Flexural strength results.

3.4 | Flexural strength

Figure 7 illustrates the variation in flexural strength among the different concrete samples with various fiber types and compositions. The standard deviation in concrete strength between the samples is shown via error bars. As illustrated, the control had the highest flexural strength of 2.87 MPa at the 28-day interval. This was a 9%, 17%, 14%, and 17% decrease in flexural strength compared to T2.5, MKT, SFKF5, and KFT, respectively. The reduced strength across all fiber composite materials demonstrates that fiber pull out has occurred. This is the second phenomenon of fiber mechanical failure in composite materials. Fiber pull-out is the debonding of fibers in their respective environment under applied loads.[61] This can occur due to inadequate bonding between the fiber and the matrix, namely weak interfacial adhesion. Smooth surface areas of the fiber can allow the fiber to have less friction resistance when the load is applied, thus enhancing the fiber to pull-out of the localized area.[62] Therefore, when integrating fibers in composite materials it is critical to ensure the interaction between the fiber and the matrix is investigated. Fernandez Ruiz et al.,[63] integrated macro-synthetic fibers (MSFs) within concrete partition walls. Their findings demonstrated the fibers stabilized the formation of cracks when under implied flexural stress. Similar to the textile fibers used in this study, the MSFs were randomly dispersed, ultimately reducing crack formation. Minimizing crack propagation can increase the durability of the composite materials, improving physical and mechanical properties. If there is insufficient compatibility between the fibers and the matrix it can create weakened stress transfers. A lack of efficient stress transfer causes localized failure at the fiber and matrix interface. Moreover, as the flexural load is applied to the fiber composite, the formation of crack propagation occurs. When cracks form around the fibers, it weakens the bond between those fibers and the matrix, thus promoting fiber pull-out to occur.

As demonstrated in Figure 7, the higher content of fiber in the concrete matrix reduces the flexural strength. This is shown with MKT and KFT that achieved the lowest strength of 2.38 MPa at 28 days. T2.5 achieved 2.62 MPa which was the highest strength for the fiber composites. Whereas SFKF5 achieved 2.46 MPa at the 28-day interval. Similar results were shown with Li et al.,[64] whom utilized natural fibers derived from bamboo in concrete. Their findings demonstrated the water absorption characteristics of the fiber increased the crack pattern of the materials. However, optimizing the number of fibers to 1.2% increased the mid-span deflection by 25.5%. It is important to note that the fibers were placed longitudinally for this increase to occur. The control has a higher flexural strength due to several factors including, homogenous structure, improved workability, optimal mix design, and reduced mechanical variabilities.[65] Concrete without fibers typically have a more uniform and homogenous structure. This allows the applied load to transfer throughout the whole matrix as one single unit. Moreover, reducing the number of raw materials in concrete will also reduce the variables associated with additional materials. When the concrete mix design is optimized between cement, water, fine and coarse aggregates, the workability can remain consistent. With the addition of fibers in concrete, the mixing process must remain uniform otherwise further variabilities will be associated with the results. However, as demonstrated with the tensile and compressive strength results, fiber integration can be beneficial. Although flexural strength is reduced, this is primarily associated with the fiber pull-out phenomenon. The four-point bending apparatus used to determine the flexural strength entails four points of applied pressure. This creates excessive loading on the four points of load transference between the matrix and the fibers. As the load increases on the concrete beams, the formulation of micro-cracks develops and crack propagation occurs. The increased dimensional changes of those cracks within the matrix creates additional voids and subsequently a porous microstructure surrounding the fiber is created. This determines the mechanical failure of the fibers in the concrete

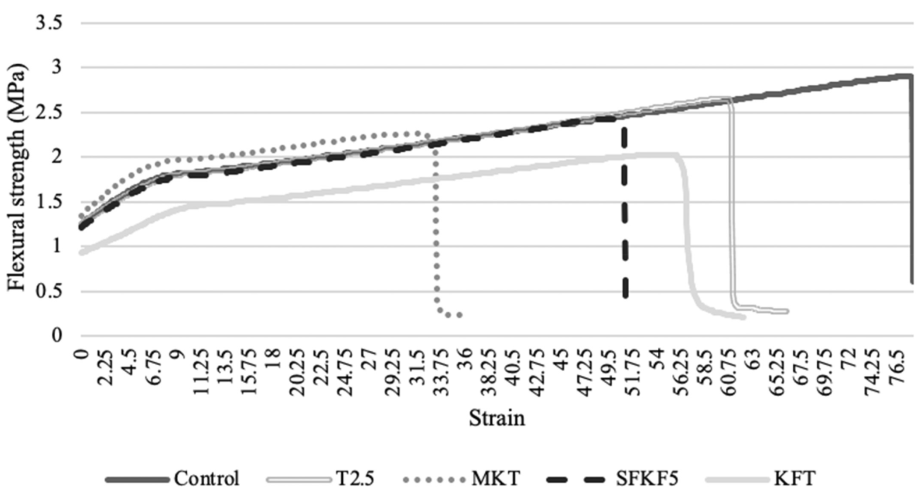


FIGURE 8 Flexural stress versus strain.

from this load application. Therefore, to enhance flexural strength in fiber concrete materials, increasing the dimensions of fibers and placing the fibers alongside the applied load can mitigate a reduction in composite strength.

Figure 8 graphically illustrates the flexural stress vs strain curve of the various mix designs. It is important to note the numerical values presented are from one of the three samples tested. The variation of maximum strength are shown via the peak curves. The flexural resistance of the control exhibited the highest strength and longest strain of the composites. MKT demonstrated mechanical failure at the shortest strain interval, whereas KFT exhibited the lowest strength but at a later load strain period. All samples had severe failure rating when the composites could not withstand the applied load. T2.5 demonstrated superior flexural resistance compared to the other fibrous composites. This could be due to the small surface areas of the fiber and the ability to agglomerate within all voids during the mixing process. T2.5 and SFKF5 maintained a similar strength incline as the control. However, the fiber composites peaked at a deflection rate of 60.75 and 51.75 mm, respectively.

4 | CONCLUSION AND FUTURE RESEARCH

This study demonstrated the mechanical and microstructural investigations of the novel concrete composites using textile and cardboard waste fibers. Microstructural analysis showed distinct differences in the surface area and behavior of SFKFs and textile fibers within the concrete matrices. These differences affected physical properties such as anchorage points, moisture absorption, petrification, and fiber–matrix interaction, thereby influencing the mechanical behavior of the composite. The experimental investigation provides valuable insights into optimizing fiber content, mix designs, and material properties to enhance composite performance. Future research studies could focus toward the economic and environmental implications when using the waste fibers in cementitious materials. Additionally, physical properties of the composite such as shrinkage, and various loading types could be further researched. The integration of the waste fiber materials in concrete presents a promising avenue to address sustainability challenges in the building and construction industry. The most important outcomes of this study are summarized as follows.

- The combination of textile and SFKFs can achieve a compressive strength of 44 MPa, which is the same as the control.
- Tensile strength is improved by 4.74% when using the combination of textile and SFKFs.
- Flexural strength is reduced by 8.71%, 17%, 14.28%, and 17% when integrating T2.5, MKT, SFKF5, and KFT, respectively.
- The use of MK can improve the mechanical stability of waste fibers in concrete via the minimization of degradation on the fiber walls.
- 5% cement replacement with SFKFs exhibited a 25% reduction in compressive strength.
- Petrification occurs at a higher rate when using natural fibers in comparison to synthetic textile materials.
- Polyester textile fibers physically bond in the concrete matrix rather than chemical bonding.
- The use of SF can enhance the durability of natural fibers in concrete by reducing the attachment of cement products in the composite matrix.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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REFERENCES

1. Amran M, Fediuk R, Abdelgader HS, Murali G, Ozbakkaloglu T, Lee YH, et al. Fiber-reinforced alkali-activated concrete: a review. J Build Eng. 2022;45:45.
2. Haigh R, Sandanayake M, Sasi S, Yaghoubi E, Joseph P, Vrcelj Z. Microstructural attributes and physiochemical behaviours of concrete incorporating various synthetic textile and cardboard fibres: a comparative review. J Build Eng. 2024;86:108690.
3. Haigh R, Sandanayake M, Bouras Y, Vrcelj Z. A life cycle assessment of cardboard waste in low stress grade concrete applications. Environ Manag. 2024;354:120428.
4. Haigh R. The mechanical behaviour of waste plastic milk bottle fibres with surface modification using silica fume to supplement 10% cement in concrete materials. Construct Build Mater. 2024;416:135215.
5. Sadrolodabaee P, Hosseini SMA, Claramunt J, Ardanuy M, Haurie L, Lacasta AM, et al. Experimental characterization of comfort performance parameters and multi-criteria sustainability assessment of recycled textile-reinforced cement facade cladding. J Clean Prod. 2022;356:356.
6. Abd SM, Mhaimeed IS, Tayeh BA, Najm HM, Qaidi S. Investigation of the use of textile carbon yarns as sustainable shear reinforcement in concrete beams. Case Stud Constr Mater. 2023;18:e01765.
7. Iyer KA, Flores AM, Torkelson JM. Comparison of polyolefin biocomposites prepared with waste cardboard, microcrystalline cellulose, and cellulose nanocrystals via solid-state shear pulverization. Polymer. 2015;75:78–87.

8. Sadrolodabaee P, Claramunt J, Ardanuy M, de la Fuente A. Mechanical and durability characterization of a new textile waste micro-fiber reinforced cement composite for building applications. Case Stud Constr Mater. 2021;14:e00492.
9. Baloch WL, Siad H, Lachemi M, Sahmaran M. A review on the durability of concrete-to-concrete bond in recent rehabilitated structures. J Build Eng. 2021;44:103315.
10. Alexander AE, Shashikala AP. Studies on the mechanical and durability performance of textile reinforced geopolymer concrete beams. Mater Today Commun. 2023;35:105837.
11. Ajayebi A, Hopkinson P, Zhou K, Lam D, Chen H-M, Wang Y. Estimation of structural steel and concrete stocks and flows at urban scale–towards a prospective circular economy. Resour Conserv Recycling. 2021;174:105821.
12. Trung Duc Pham L, Woo U, Choi K-K, Choi H. Tensile characteristics of carbon textile-reinforced mortar incorporating short amorphous metallic and nylon fibers under designed environmental conditions. Construct Build Mater. 2022;352:129059.
13. Khan M, Ali M. Use of glass and nylon fibers in concrete for controlling early age micro cracking in bridge decks. Construct Build Mater. 2016;125:800–8.
14. Pešić N, Živanović S, Garcia R, Papastergiou P. Mechanical properties of concrete reinforced with recycled HDPE plastic fibres. Construct Build Mater. 2016;115:362–70.
15. Yang J-M, Shin H-O, Yoon Y-S, Mitchell D. Benefits of blast furnace slag and steel fibers on the static and fatigue performance of prestressed concrete sleepers. Eng Struct. 2017;134:317–33.
16. Luoma P, Penttinen E, Tapio P, Toppinen A. Future images of data in circular economy for textiles. Technol Forecast Soc Change. 2022;182:121859.
17. Khan MI, Wang L, Padhye R. Textile waste management in Australia: a review. Resour Conserv Recycling Adv. 2023;18:200154.
18. Igini M. 10 concerning fast fashion waste statistics. 2022 [Accessed on May 10, 2023]. Available from: https://earth.org/statistics-about-fast-fashion-waste/
19. Cezario M. Textile waste: how bad is the situation and how can we solve it? 2020 [Accessed on 2nd June 2023]. Available from: https://thesocialoutfit.org/blogs/the-social-journal/textile-waste-how-bad-is-the-situation-and-how-can-we-solve-it
20. Moazzem S, Wang L, Daver F, Crossin E. Environmental impact of discarded apparel landfilling and recycling. Resour Conserv Recycling. 2021;166:105338.
21. Nations U. Global issues- population. 2022 [cited August 14, 2022]. Available from: https://www.un.org/en/global-issues/population
22. Rawat P, Liu S, Guo S, Zillur Rahman M, Yang T, Bai X, et al. A state-of-the-art review on mechanical performance characterization and modelling of high-performance textile reinforced concretes. Construct Build Mater. 2022;347:128521.
23. Islam MJ, Ahmed T, Imam SMFB, Islam H, Shaikh FUA. Comparative study of carbon fiber and galvanized iron textile reinforced concrete. Construct Build Mater. 2023;374:130928.
24. Preinstorfer P, Yanik S, Kirnbauer J, Lees JM, Robisson A. Cracking behaviour of textile-reinforced concrete with varying concrete cover and textile surface finish. Compos Struct. 2023;312:116859.
25. Ibrahim AM, Abd SM, Hussein OH, Tayeh BA, Najm HM, Qaidi S. Influence of adding short carbon fibers on the flexural behavior of textile-reinforced concrete one-way slab. Case Stud Construct Mater. 2022;17:e01601.
26. Pickin J, Wardle C, O'Farrell K, Stovell L, Nyunt P, Guazzo S, et al. National waste report 2022. Docklands: The Department of Climate Change, Energy, the Environment and Water; 2022.
27. Harry Dempsey JE. Pandemic delivers transformation for packaging industry. 2021 [Accessed on June 11, 2023]; Available from: https://www.ft.com/content/dfafff92-9e37-4fa4-ab29-ba4c6ea4f1ef
28. Haigh R, Sandanayake M, Bouras Y, Vrcelj Z. The durability performance of waste cardboard kraft fibre reinforced concrete. J Build Eng. 2023;67:106010.
29. Chakar FS, Ragauskas AJ. Review of current and future softwood kraft lignin process chemistry. Indust Crops Prod. 2004;20(2):131–41.
30. Haigh R, Sandanayake M, Bouras Y, Vrcelj Z. A review of the mechanical and durability performance of kraft-fibre reinforced mortar and concrete. Construct Build Mater. 2021;297:123759.
31. Coutts RSP. A review of Australian research into natural fibre cement composites. Cem Concr Compos. 2005;27(5):518–26.
32. Khorami M, Ganjian E. The effect of limestone powder, silica fume and fibre content on flexural behaviour of cement composite reinforced by waste Kraft pulp. Construct Build Mater. 2013;46:142–9.
33. Booya E, Ghaednia H, Das S, Pande H. Durability of cementitious materials reinforced with various Kraft pulp fibers. Construct Build Mater. 2018;191:1191–200.
34. Haigh R, Joseph P, Sandanayake M, Bouras Y, Vrcelj Z. Thermal characterizations of waste cardboard kraft fibres in the context of their use as a partial cement substitute within concrete composites. Materials. 2022;15:8964.
35. Mohr BJ, Biernacki JJ, Kurtis KE. Microstructural and chemical effects of wet/dry cycling on pulp fiber–cement composites. Cem Concr Res. 2006;36(7):1240–51.
36. Savastano H, Santos SF, Radonjic M, Soboyejo WO. Fracture and fatigue of natural fiber-reinforced cementitious composites. Cem Concr Compos. 2009;31(4):232–43.
37. Tonoli GHD, Belgacem MN, Siqueira G, Bras J, Savastano H, Rocco Lahr FA. Processing and dimensional changes of cement based composites reinforced with surface-treated cellulose fibres. Cem ConcrCompos. 2013;37:68–75.
38. Haigh R, Bouras Y, Sandanayake M, Vrcelj Z. The mechanical performance of recycled cardboard kraft fibres within cement and concrete composites. Construct Build Mater. 2022;317:125920.
39. Haigh R, Bouras Y, Sandanayake M, Vrcelj Z. Economic and environmental optimisation of waste cardboard kraft fibres in concrete using nondominated sorting genetic algorithm. J Clean Prod. 2023;426:138989.
40. AS/NZS-3582.3. Supplementary cementitious materials. Part 3: Amorphous silica. Sydney: Australian Standards; 2016.
41. ASTM-C-618. Standard specification for coal fly ash and raw or calcined natural pozzolan for use in concrete. West Conshohocken, PA: American Society Testing & Materials; 2019.
42. AS/NZS-3972. General purpose and blended Cements. Sydney: Australia Standards; 2010.

43. AS/NZS-1141.6.2. Methods for sampling and testing aggregates- particle density and water absorption of coarse aggregate-pycnometer method. Sydney: Australia Standards; 2016.
44. AS/NZS-1141.5. Methods for sampling and testing aggregates-particle density and water absorption of fine aggregate. Sydney: Australia Standards; 2000.
45. AS/NZS-1012.2. Methods of testing concrete Preparing concrete mixes in the laboratory. Sydney: Australia Standards; 2014.
46. AS/NZS-1012.3.1. Methods of testing concrete. Determination of properties related to the consistency of concrete- slump test. Sydney: Australia Standards; 2014.
47. AS/NZS-1012.8.2. Methods of testing concrete. Method for making and curing concrete – flexure test specimens. Sydney: Australia Standards; 2014.
48. AS/NZS-1012.9. Methods of testing concrete. Method 9: compressive strength tests- concrete, mortar and grout specimens. Sydney: Australia Standards; 2014.
49. AS/NZS-1012.10. Methods of testing concrete. Method 10: determination of indirect tensile strength of concrete cylinders ("Brazil" or splitting test). Sydney: Australia Standards; 2000.
50. AS/NZS-1012.11. Methods of testing concrete. Determination of the modulus of rupture. Sydney: Australia Standards; 2000.
51. Samuelsson LN, Babler MU, Brännvall E, Moriana R. Pyrolysis of kraft pulp and black liquor precipitates derived from spruce: thermal and kinetic analysis. Fuel Process Technol. 2016;149:275–84.
52. Souza MT, Onghero L, Sakata RD, Neto FC, de Campos CEM, de Castro Pessôa JR, et al. Insights into the acting mechanism of ettringite in expansive Portland cement. Mater Lett. 2023;345:134496.
53. Mohan A, Madhavi TC. Flexural behavior of warp knitted textile reinforced concrete impregnated with cementitious binder. Case Stud Constr Mater. 2024;20:e02884.
54. Haigh R. A decade review of research trends using waste materials in the building and construction industry: a pathway towards a circular economy. Waste. 2023;1(4):935–59.
55. Haigh R. A comparitive analysis of the mechanical properties with high volume waste cardboard fibres within concrete composite materials in Australasian structural engineering conference: ASEC 2022. Melbourne, Australia: Engineers Australia; 2022.
56. Patil S, Sudarsana Rao H, Ghorpade VG. The influence of metakaolin, silica fume, glass fiber, and polypropylene fiber on the strength characteristics of high performance concrete. Mater Today Proc. 2023;80:577–86.
57. Narule GN, Ulape YB. Performance on steel fiber reinforced concrete using metakaolin. Mater Today Proc. 2023.
58. Chen JJ, Ng PL, Chu SH, Guan GX, Kwan AKH. Ternary blending with metakaolin and silica fume to improve packing density and performance of binder paste. Construct Build Mater. 2020;252:119031.
59. Alan Strauss Rambo D, Umbinger de Oliveira C, Salvador RP, Filho RDT, da Fonseca Martins Gomes O, de Andrade Silva F, et al. Sisal textile reinforced concrete: improving tensile strength and bonding through peeling and nano-silica treatment. Construct Build Mater. 2021;301:124300.
60. Li R, Deng M, Guo L, Wei D, Zhang Y, Li T. Tensile behavior of high-strength highly ductile fiber-reinforced concrete with embedded carbon textile grids. Construct Build Mater. 2024;414:134957.
61. Tayfur S, Alver N, Abdi S, Saatcı S, Ghiami A. Characterization of concrete matrix/steel fiber de-bonding in an SFRC beam: principal component analysis and k-mean algorithm for clustering AE data. Eng Fracture Mech. 2018;194:73–85.
62. Hu S, Han P, Meng C, Yu Y, Han S, Wang H, et al. Comparative study of different bonding interactions on the interfacial adhesion and mechanical properties of MXene-decorated carbon fiber/epoxy resin composites. Compos Sci Technol. 2024;245:110352.
63. Fernández Ruiz M, Redaelli D, Nogales Arroyo A, Monserrat-López A, Bourqui D, de la Fuente Antequera A. Macrosynthetic fibers as replacement of conventional steel reinforcement for concrete of partition walls. Struct Concr. 2024;25:1031–51.
64. Li H, Feng Z, Sayed U, Adjei P, Xue X, Wang Z, et al. Flexural performance of bamboo fiber-reinforced concrete mixed with seawater and sea sand. Struct Concr. 2024;100:1–18.
65. Lai Z, Zhou W, Yang X, Wang Y. Flexural behavior of high-strength square concrete-filled steel tube members subjected to cyclic loadings. Structure. 2023;58:105413.

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