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Mechanical properties and life cycle greenhouse gas analysis of textile waste fibre-based concrete

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ABSTRACT

The application of textile waste as an aggregate in concrete enhances sustainability in construction and promotes circular economy. This work develops a novel fibre-based concrete incorporating textile waste fibres. The experiments showed that including textile waste fibres reduces flowability of concrete and improves its tensile and compressive strengths, alongside strain resistance. The fibres enhance concrete's ductility and resilience against environmental damage. Textile waste fibre exhibits a lower greenhouse gas emissions compared to other non-polymer fibres. This work emphasises the benefits of textile waste in enhancing construction sustainability and highlights the need for expanded exploration.

1. Introduction

Australia is the second-largest textile consumer per capita in the world, behind the United States of America. Overproduction and underutilisation of garments are fundamental underlying issues. Each Australian consumes 27 kg of new apparel annually on average [1]. Textile waste includes not just "post-consumer clothes" but also "post-industrial sources" along with hotel linen, furniture, upholstery, and uniforms. Consequently, material consumption and waste generation because the textile industry has become an environmental concern. The textile industry is the second largest industrial polluter accounting for 10% of greenhouse gas (GHG) emissions and 20 % of wastewater disposal [2,3]. Main waste products from the textile industry comprise fibrous blended waste of natural and synthetic fibres and contaminated wastewater and chemicals. The production, consumption, and post-consumer treatments of synthetic textiles manufactured from fossil fuels as feedstock have negative effects on the environment in terms of GHG emissions and waste disposal. Natural fibres like cotton also have considerable effects on the environment related to pesticide, irrigation water, and usage of agricultural machinery in production [4]. Synthetic fibre production accounted for approximately 64 % of global textile fibre volume, whereas Polyester alone has accounted for 54 % [5]. With the movement for more sustainable industries and products, textile manufacturing is also forced to find new avenues for reducing consumption and waste while increasing reuse and recycling. The linear method of apparel consumption is no longer sustainable and should move toward a circular economy model based on product design and development, waste management, and effective recycling [6]. However, the recycling of textile account for only 13 % globally, whereas the rest is sent for landfill or incineration [7]. The CO_2 equivalent emissions of landfills are reported to be higher than virgin fibre production, so recovery of textile waste can help in reducing total greenhouse gas emissions. Furthermore, textile reuse refers to the extending of the actual service life of the product, while recycling refers to reprocessing of pre or post-consumer textiles into new products [8]. Textile recycling routes may comprise mechanical, chemical, and thermal processes and reduce the environmental impacts compared with incineration and landfilling. Sadin and Peters [8] argued that reuse is more beneficial than recycling because of the avoidance of the creation of new products. However, more inventory data is required for recycled materials.

Reduction of raw material consumption with the usage of waste or recycled materials is widely accepted in producing greener products for a more sustainable future. Reused or recycled materials help to extend and circulate the extracted raw materials in the economy. Matasci et al. [9] have performed material flow analysis and simplified life cycle assessment to increase the circularity of the Swiss economy. Concrete

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has been identified as a material consumed and disposed of at a high level, whereas textiles carry the biggest burden on the environment during its extraction and production. Applications of textile waste as thermal and acoustic insulations in the building have been studied in the literature [10,11]. The insulation properties, fibre morphology, resistance to fire, fungi, and moisture are stated as areas that need further studies with insulation materials made with various textile waste fibres. Textile fibre-based composites from mixed fibre feedstock for building applications as a low-carbon alternative have shown comparable results with standard wood-based particleboards [3]. Concrete, as a heavily used construction material, can claim mutual benefits from being considered for circular approaches with textile waste [12]. Research into recycled fibre-based concrete (RFRC) has been growing rapidly in recent years where plastics and Polypropylene and Nylon are the most studied fibres [7]. Studies with waste-originated fibres such as rubber, plastic, steel, glass, and carbon with self-compacting concrete (SCC) have shown reduced workability, and limited or inconsistent results on flexural, impact, and durability characteristics [13]. Inconsistent dispersion of fibres and reduced workability at high concentrations of waste natural fibres in cementitious composites were observed by Li et al. [14]. A review of macro plastic fibres in concrete by Yin et al. [15] has shown they can offer cost and environmental benefits compared with traditional steel fibres. Improved ductility at the post-crack region, effective control of plastic shrinkage cracking despite the reduced workability, and improved bonding strength were reported as positives. Similar findings on lower compressive strength but improved tensile and flexural strength were reported in some studies [16–18]. Contrasting findings were also reported where authors claim improved strength properties [19–21]. Mohammadhosseini et al. [22] claimed that compressive strength gain at ultimate curing ages is more prominent for concrete with waste industrial carpet fibres. A study of recycled plastic, steel, and carpet fibres on fresh, mechanical, and ductility properties by Ahmed et al. [23] showed improved tensile and flexural strength and highlighted the importance of the durability properties of the composites. The properties of cementitious composites with textile waste highly depend on the fibre type, length, and volume fractions, and studies with mixed fibre contents are hardly reported. Furthermore, the performance of these recycled fibres at elevated temperatures also needs to be investigated.

Most of the applications of textile waste in concrete require mechanical or thermal pre-treatments and separation into singular fibre types [2]. This could be a time and money-consuming effort and often presents limitations with blended fibre composites. Thermal pre-treatments present challenges in quality outputs which need to be further researched [4]. Textile processing involves heavy chemical processes that will impose limitations on its usage after recycling. Furthermore, the degrading limits of plastic fibres because of recycling cycles also pose limitations on their applicability [3]. Textile cuttings or strips can cease the need for separation into fibres from waste fabrics and minimal handling can limit the damage to fibres. Furthermore, the utilisation of blended waste can eliminate the investment in the sorting phase. The disposal or recycling of post-consumer textile waste needs to be further studied to assess the sustainability of the proposed pathways. The main aim of this study is to investigate the effects of post-consumer textile waste on the mechanical properties of concrete and the life cycle greenhouse gas analysis of textile waste fibre. Fabric cuttings were used to eliminate the separation and sorting process of textile fibres. Different percentages of textile waste fibre content are mixed with concrete and evaluated for their properties. A detailed investigation into the textile waste (end-of-life phase) is being made to understand the life cycle of this novel recycled product. The insights gained from this study are expected to help in developing sustainable cementitious composites while overcoming the main hindrances faced in the textile waste recycling industry.

2. Materials and methods

2.1. Materials properties and mix design

Waste fabric samples used in this study were obtained from waste cut pieces in a local garment manufacturing company. The waste-knitted fabrics were in a different range of dimensions and some of the common properties are presented in Table 1. The composition of the waste fabrics was determined based on EU 1007/2011 and ISO1833[24,25]. Determination of the elasticity of the fabrics was performed based on ISO 20932–1 [26] Higher recovery in elongation was observed in the warp direction compared to the weft in the fabrics. All fabric samples were cut into 20 mm×20 mm pieces prior to their addition to the concrete mix as shown in Fig. 1.

The materials used in this study comprised Grade 43 Ordinary Portland Cement (OPC), river sand, and two types of crushed natural coarse aggregate with a maximum nominal size of 20 mm. The basic properties of OPC are shown in Table 2. A polycarboxylate-based superplasticizer (PCE) was also included in the concrete mix to improve its workability. To facilitate testing on both fresh and hardened concrete, four distinct mix designs were created. The water-to-binder ratio for all four mixtures was held constant at 0.45, with 451.5 kg/m^3 cement content and 203 kg/m^3 of water. A detailed breakdown of each mix's proportions can be found in Table 3. For this study, three concrete mixes were created. The initial mix served as the control batch and did not contain any textile. The subsequent two mixtures had varying fibre volume fractions of 1.0% and 1.5%, with the fibre content replacing the sand content accordingly.

2.2. Mixing procedure

A concrete mixer with a volume of 30 dm^3 was used to prepare textile-based concrete. Sand and coarse aggregates were first added in the mixer and stirred at 60 rpm for 1 min, and GP cement was then incorporated into the dry aggregates at 60 rpm for 2 min. Subsequently, water and PCE were poured into the dry mixture at 60 rpm for 2 min until homogeneous concrete with good workability was produced. Then, textile fibres were mixed with the fresh concrete at 60 rpm for 2 min to disperse the fibres uniformly. At last, the fresh textile concrete was cast into cylinder moulds (d=100 mm, h=200 mm). After curing for 24 h in moulds covered with plastic film, the specimens were demoulded and placed into water, with relative humidity set at ≥95 % and temperature at 20 ± 2 C.

2.3. Methods

2.3.1. Concrete properties testing

The fresh state properties of each mix were evaluated through slump tests in accordance with AS 1012.3.1:2014. Cylindrical specimens were prepared for the splitting tensile strength tests in accordance with AS 1012.10–2000. Compressive strength was measured at a loading speed of 3 kN/s, in accordance with AS 1012.9:2014. Deformation capacity and toughness were obtained from the compressive load-displacement curve, one linear variable displacement transducer (LVDT) attaching to the compression board, as shown in Fig. 2. These mechanical tests were conducted at both 7 and 28 days to assess the strength development of each mix over time.

Table 1
Engineering properties of textile waste fabrics.

Composition	Density (kg/m^3)	Modulus @ 40 % (N)		Melting point (°C)	Reaction with water
		Warp	Weft		
95 % Polyester & 5 % Elastane	40	0.617	0.492	250	Hydrophobic

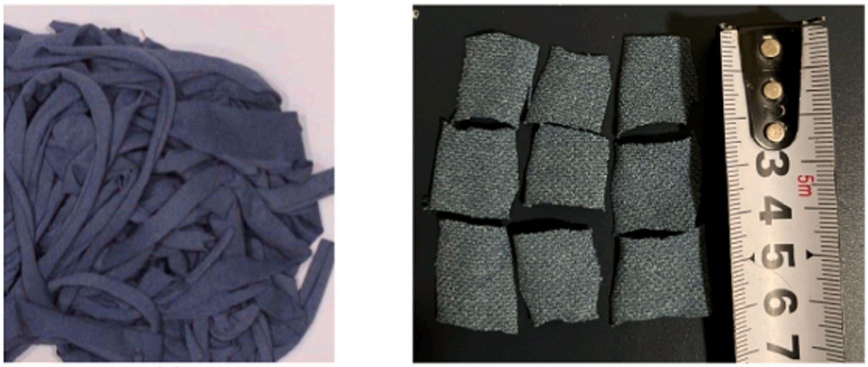

(a) (b)

Fig. 1. (a) Waste fabric pieces from manufacturer; (b) Prepared waste fabric pieces 20 ×20 mm.

Table 2
Basic properties of OPC.

Cement	SSA (m_2/kg)	Setting time /min		Compressive strength/ MPa		
		Initial setting	Final setting	3d	7d	28d
PC	375	215	383	30.1	43.8	59.3

Note: SSA represents specific surface area

Table 3
Mix design (kg/m^3).

Component	Textile 0.0 %	Textile 1.0 %	Textile 1.5 %
General purpose cement	451.5	451.5	451.5
Coarse aggregate (7 mm)	581.7	581.7	581.7
Coarse aggregate (14 mm)	581.7	581.7	581.7
Sand	573.3	567.6	564.7
Water	203.0	203.0	203.0
Polycarboxylate-based superplasticizer	2.3	2.3	2.3
Textile	0.0	2.0	3.0

Fig. 2. Setup of compression test.

2.3.2. *Life cycle greenhouse gas analysis of textile waste*

To assess the environmental impact of textile fibres, a comprehensive analysis of all processes involved in obtaining textile waste fibres from an apparel company is conducted, focusing on environmental indicators. This approach facilitates a comparison between the environmental footprint of recycled textile fibres and other fibres with similar properties, both recycled and virgin, commonly employed in concrete applications. The evaluation of the environmental impact is conducted using the widely accepted LCA method. LCA proves to be a valuable tool for quantifying environmental pressures and benefits, identifying trade-offs, and identifying areas for potential improvements by considering the entire life cycle of the product [27]. In accordance with the international standards ISO 14040 [28] and ISO 14044 [29], LCA analysis involves quantifying the environmental benefits (or impacts) associated with a product, system, or service throughout its life cycle [30]. This assessment comprises four steps: Firstly, goal and scope declaration, wherein the study's purpose and system boundaries are defined. Secondly, life cycle inventory (LCI) analysis, during which input and output data are collected and analysed in relation to the functional unit, representing the output under evaluation. Thirdly, life cycle impact assessment (LCIA), which determines the environmental impact of the product/system. Fourth, interpretation, involving the evaluation of results, drawing conclusions, and formulating recommendations.

3. Results and discussion

3.1. *Workability*

The results of the slump tests conducted on the concrete mixtures are presented in Fig. 3. The findings show that the flowability of fresh concrete decreased as the textile content increased. The maximum slump value of 105 mm was achieved for the control mixture, while the minimum slump value of 85 mm was observed for the mix with the highest textile fraction (1.5 %). This is mainly because more textiles absorb more water during the mixing process, reducing the flowability of the fresh mortar.

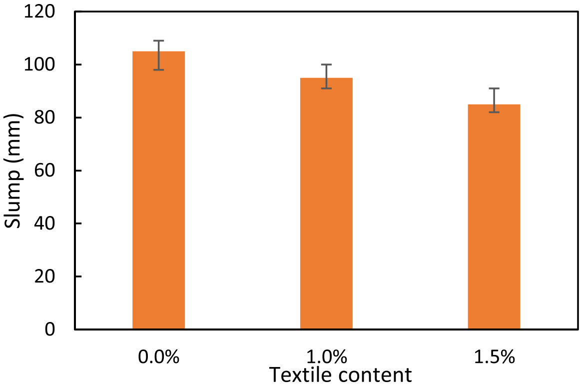


Fig. 3. Flowability of fresh textile concrete.

3.2. Splitting tensile strength

Splitting tensile strength testing showed a significant increase in the strength of concrete specimens containing textile waste compared to the control concrete with no textile. At 7 days age, the splitting tensile strength of textile concrete mixes containing 1.0 %, and 1.5 % textile increased by 11 %, and 9 %, respectively. Similarly, at 28 days, the mixes containing 1 %, and 1.5 % textile waste increased the splitting tensile strength by 9 %, and 8 %, respectively, as illustrated in Table 4. The increased tensile strength can be attributed to the textile fibres bridging the split parts of the specimens, transferring the stress from the matrix to the fibres, and supporting the full tensile stress gradually.

Table 4
Tensile strength of textile concrete.

Textile Content	7 days		28 days	
	Tensile Strength (MPa)	Difference (%)	Tensile Strength (MPa)	Difference (%)
0.0%	3.0	-	3.3	-
1.0%	3.4	11%	3.6	9 %
1.5%	3.3	9%	3.5	8 %

3.3. Compressive properties

Fig. 4 illustrates the compressive stress-stain curves of textile-reinforced concrete with different textile contents. It is evident that both the 7-day and 28-day age groups with the addition of textile exhibit significant strain hardening behaviour, where the curves become smoother after reaching the peak point, and the corresponding stain at the highest strength is also greater. Based on these characteristics, a more detailed analysis of the stress-strain curves is conducted, resulting in Table 5. In this table, ε_{cu} is the peak strain corresponding to the peak stress (fc); ε_0 indicates the ultimate strain, corresponding to the falling section of the curve when the stress is $0.5\,fc$ [31]; S1 and S2 of the toughness index stand for the area between the stress–strain curve and the x-axis, when the strain are 3 ε_{cu} and ε_{cu} respectively [32].

It can be observed from Fig. 5 and Fig. 6 that with an increasing amount of textile inclusion, both the 7-day and 28-day compressive strengths and the corresponding strain of the specimens continuously increase. Particularly, during the 7-day age period, the peak strain significantly increases from 0.467×10^{-3} to 2.971×10^{-3} as the textile content increases from 0.0 % to 1.5 %. Thus, it can be concluded that textile provides a significant enhancement and toughening effect. Strength increase can be attributed to two factors. First, the porous nature of the textile, which absorbs some water during specimen formation, leads to a reduction in the water-to-cement ratio, increasing the compressive strength. Second, the textile acts as an internal curing agent, and releases free water from its structure after the hardening of the specimen. This promotes the hydration of concrete and enhancing its strength [33]. Moreover, the increase in peak strain is due to the bridging effect of the elastic textile with high tensile strength, slowing down the internal structural damage during the compression process and thus improving the energy absorption and toughness of the concrete. It is worth noting that a significant increase in compressive strain occurred in the sample with 1.5 % textile content at 7 days. Firstly, the fibres' water absorption during the early hydration stage increases. The increase in fibre content reduces the water-to-cement ratio, thereby enhancing the interfacial bond strength between the fibres and the matrix. Secondly, the increased fibre content enhances the bridging capability during matrix fracture. Since tensile strain does not linearly increase with fibre content, the substantial increase in compressive strain indicates that 1.5 % is a highly suitable fibre content.

To comprehensively investigate the impact of textile fibres on the deformation capacity and toughness of concrete, quantitative evaluations were conducted using the $\varepsilon_0/\varepsilon_{cu}$ and toughness index, as illustrated in Figs. 7 and 8, respectively. The higher the values, the greater the deformation capacity and toughness of textile-reinforced concrete are [34]. It suggests that concrete specimens incorporating textile fibres at various ages exhibited significantly higher values of $\varepsilon_0/\varepsilon_{cu}$ and toughness index compared to the non-fibre-based concrete, which indicates that textiles, owing to their exceptional tensile properties and bridging effect within the concrete matrix, enhance the ductility of concrete and increase its energy absorption capacity under external environmental damage.

Moreover, at 7 days of age, the textile-based concrete with a 1% fibre content demonstrated the highest $\varepsilon_0/\varepsilon_{cu}$ and toughness index, while at 28 days, the maximum values were observed in the concrete with a 1.5 % fibre content. This phenomenon can be mainly attributed to: At the age of 7 days, the 1.5 % fibre content causes textile fibres to absorb excessive moisture, thereby reducing the hydration degree of the matrix at 7 days. Consequently, compared to the 1 % fibre content, it exhibits a lower deformation capacity. However, by the age of 28 days, the 1.5 % fibre content samples release more moisture from textile fibres, further participating in hydration reactions, improving the bonding performance between fibres and the matrix. Therefore, both the deformation capacity and toughness index of the samples at 28 days in Figs. 7 and 8 are maximised.

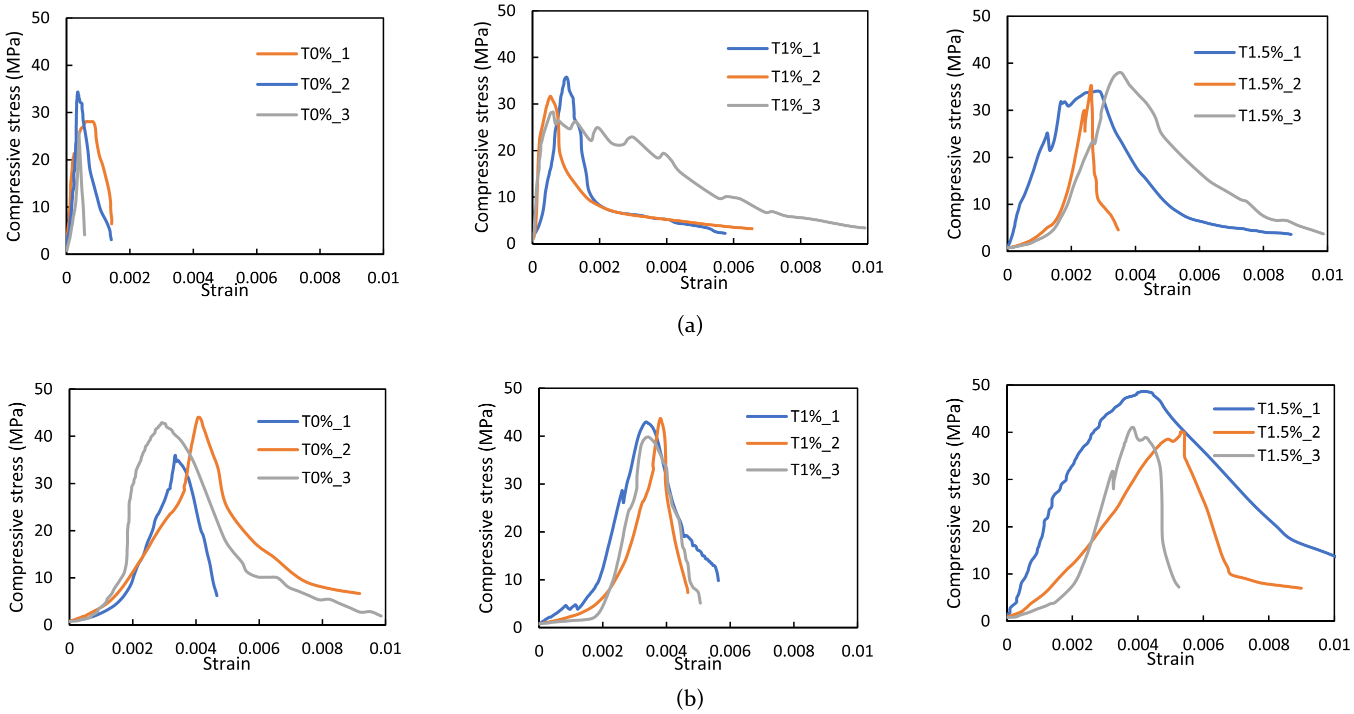
While the increase in strength and toughness properties of concrete with the addition of comparatively small amounts of textile will be welcome from the construction industry, it is important to assess the effects of addition of textile materials on the durability and serviceability properties of concrete. It is likely that weathering and faster deterioration of the fibres reduce the overall properties of concrete. One additional concern regarding the increased toughness of the material is the processing of end-of-life (EoL) of fibre-based concrete. Processing the fibre-based concrete will require additional energy to separate, when compared to the reference concrete. Even then, the recycled aggregates and the mortar matrix will come synthetic and other fibre types (depending on the source of the fabric) which will be challenging to recirculate.

3.4. Life cycle analysis (LCA)

Australia stands out as the OECD member country, generating the most significant amount of commercial and industrial textile waste per capita [1]. Unfortunately, the country also exhibits the lowest percentage of waste recovery across all waste types, with a staggering 87.5% of textile waste ending up in landfills. This high volume of textile waste in landfills contributes significantly to global warming [35]. Hence, the recycling and re-utilisation of textile waste has become exceptionally imperative.

One effective approach for repurposing textile waste involves its incorporation into concrete, as this not only uses waste materials for constructing new structures but also conserves energy and reduces the environmental impact of concrete by substituting conventional concrete ingredients. Prior to incorporation, mechanical treatment is often necessary to reduce the size of the textile waste. Compared to incineration, mechanical recycling considerably lowers primary energy consumption and greenhouse gas emissions. Furthermore, mechanical recycling proves to be a low-cost process, consuming far less energy compared to alternative recycling methods like chemical recycling and pyrolysis [36]. Utilising textile waste in concrete manufacturing leads to a reduced environmental footprint. For instance, the extraction of fine aggregates from riverbeds, a non-sustainable practice, can be mitigated through incorporating textile wastes into concrete [37]. As a result, incorporating textile waste into concrete shows a promising avenue.

To assess the potential of the mechanical treatment for textile waste, this study conducted a comprehensive lifecycle greenhouse gas analysis and financial assessment on various recycling methods for textile waste and compared them with other waste types incorporated into concrete.



(a)

(b)

Fig. 4. Compressive stress-strain curves of textile reinforced concrete: (a) 7 days, (b) 28 days.

Table 5
Characteristic values of the stress-strain curves of the textile-reinforced concrete specimens.

Age (day)	Textile content	*fc* (MPa)	ε_{cu} (10^{-3})	$\varepsilon_0/\varepsilon_{cu}$	Toughness index (S1/S2)
7	0.0%	29.4 ±3.6	0.467 ±0.110	1.25 ±0.19	2.28±0.45
	1.0%	31.9 ±3.6	0.721 ±0.185	3.51 ±0.83	2.98±0.42
	1.5%	33.2 ±4.8	2.971 ±0.111	1.36 ±0.23	2.84±0.5
28	0.0%	41.0 ±3.1	3.460 ±0.791	1.39 ±0.17	2.62±0.55
	1.0%	42.1 ±1.6	3.524 ±0.551	1.60 ±0.02	3.10±0.10
	1.5%	43.3 ±3.2	4.462 ±0.878	1.68 ±0.25	3.44±0.30

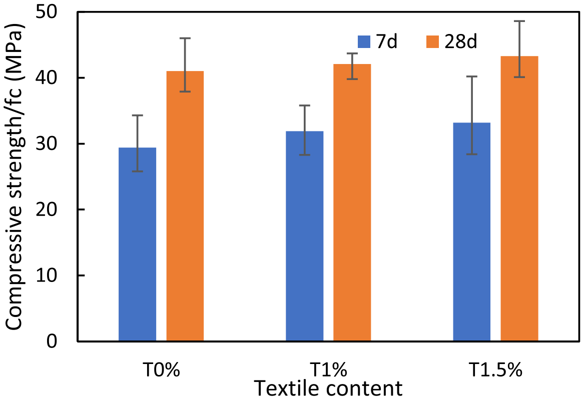


Fig. 5. Compressive strength vs textile content.

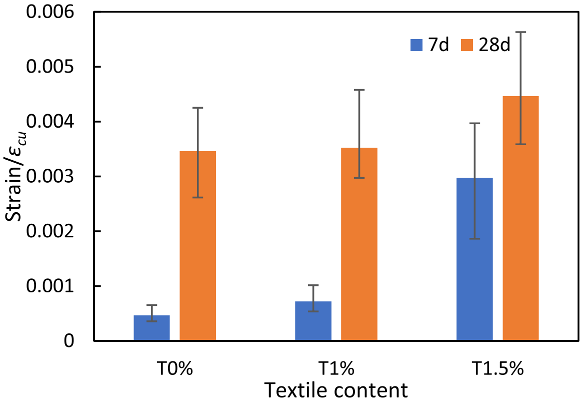


Fig. 6. Compressive strain vs textile content.

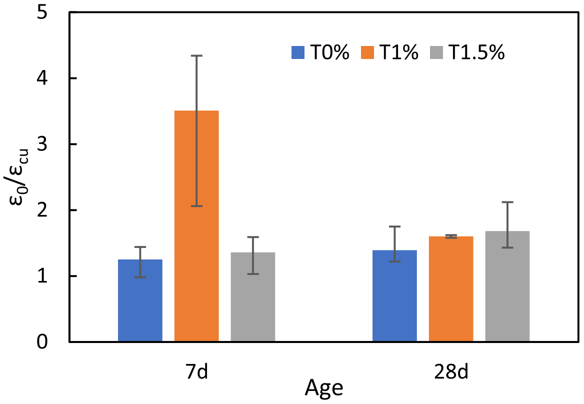


Fig. 7. Deformation capacity vs textile content.

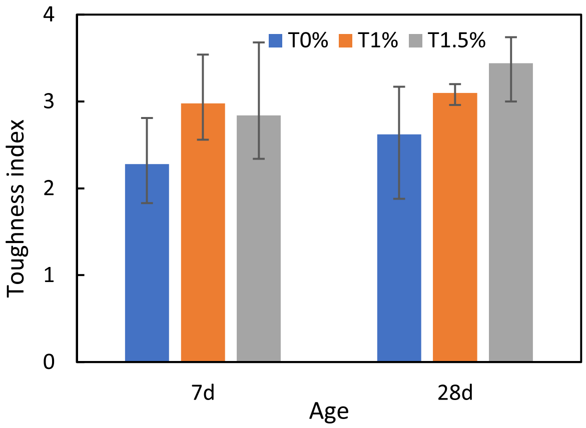


Fig. 8. Toughness index vs textile content.

3.4.1. *Goal and scope definition*

The utilisation of LCA proves to be a viable and adaptable method to evaluate the environmental benefits associated with recycling textile fibres from disposed apparel and their subsequent incorporation as reinforced fibres into a cementitious composite matrix. In this study, a functional unit of 1 kg of textile fibres is established, with all inputs and outputs expressed per kg of textile fibre product, ready for dispersion within the cementitious matrix.

Compared to other types of fibre-based concrete and considering the consistency of other raw materials, such as cement, aggregates, and mineral admixtures used in textile-reinforced concrete, as well as the uniformity in concrete construction and operational processes (e.g., construction and maintenance), these factors have been deemed to be outside the scope of the analysis to simplify the LCA processes. This approach is in line with a similar study [38].

Textile waste, as a part of the closed loop in the apparel industry, is considered to be in the end-of-life state. However, when it is repurposed as an internal reinforcement fibre in concrete, it becomes part of the entire lifecycle of concrete, representing its cradle state. Therefore, the recycling and utilisation of textile waste hold significant importance, granting textiles a new lease on life. The process of recycling textile waste is illustrated in Fig. 9.

The collection and transportation of textile waste to the processing plant involve an average transport distance of 300 km. Each truck has a carrying capacity of 2000 kg. Diesel fuel consumption for articulated truck was assumed to be 53.1 L per 100 km in Australia [39]. Upon arrival at the plant, the apparel undergoes washing with water to remove soil and sand, and mechanical sorting is employed to separate individual components, primarily plastic buttons, and small pieces of wood. The processing plant operates with a throughput of approximately 300 kg/h and functions in an almost closed cycle. Following the sorting process, the textile waste is subjected to a textile heater machine for drying, with a working efficiency of 300 kg/h. Subsequently, the dried textile waste is shredded into fibres suitable for concrete, with an approximate throughput of 250 kg/h. The shredded fibres are then compacted and packed into large bags at an approximate throughput of 1000 kg/h. Table 6 provides the details of the machines utilised for textile recycling and their characteristics [40].

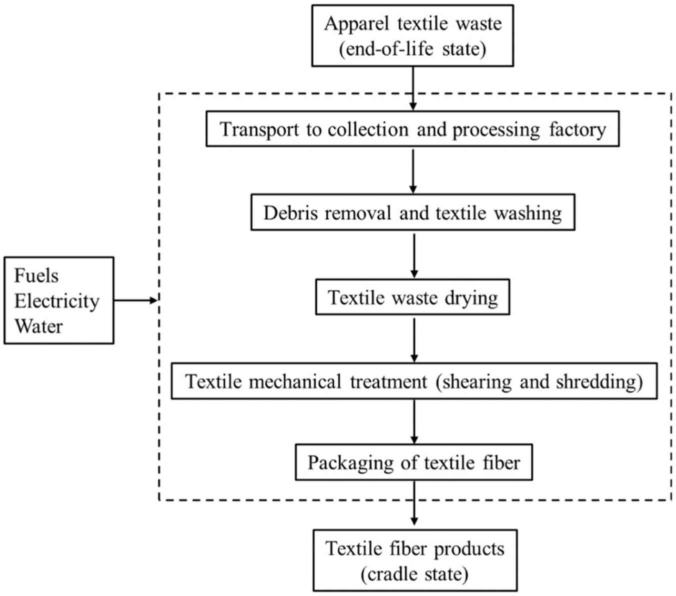


Fig. 9. The process of recycling textile waste.

It is important to note that auxiliary processes aimed at recovering non-fibre materials, such as sand, garment accessories, and decorative wood chips, are considered being outside the system boundary and are not considered in the analysis.

3.4.2. *Life cycle inventory (LCI)*

For the LCI phase of this study, primary data were employed, which were directly obtained through on-site investigations and through communication with a local garment manufacturing company involved in textile waste collection and treatment. Background data, including information on electricity, gasoline, and carbon emission factors, were sourced from reputable databases such as ecoinvent version 3.5, SimaPro 8.0, and Australian LCA databases [38,45,46]. These databases provide comprehensive and reliable data on various environmental factors and inputs commonly used in life cycle assessments.

3.4.3. *Life cycle impact assessment (LCIA)*

LCIA involves estimating indicators of environmental pressures, such as climate change, summer smog, resource depletion, acidification, human health effects, and more, associated with the environmental interventions throughout the life cycle of a product. To conduct the LCIA, the software SimaPro 9.0 is utilised, which facilitates the calculation and analysis of these environmental impacts.

For this study, the environmental impact analysis focuses primarily on GHG emissions, a significant indicator. Carbon dioxide equivalent (kg CO_2-e) is a standard unit for measuring GHG emissions. The fossil fuel consumption includes both direct usage of fossil energy sources and the energy generated from the conversion of fossil fuels to electricity, and GHG emission is calculated based on the energy carbon emission factors, allowing for a comprehensive assessment of the environmental implications associated with the recycling and utilisation of textile waste throughout its life cycle. The textile recycling facility is assumed to be in Victoria, Australia. The national greenhouse emission factors were used to estimate the emission factors related to diesel fuel and electricity consumptions.

3.4.4. *Interpretation*

Table 7 presents the diesel fuel and electricity consumption and GHG emissions associated with producing 1 kg of textile fibre through different mechanical processing steps. During the transportation stage, the primary fossil fuel consumption is attributed to diesel used by trucks. In contrast, in the other textile waste processing stages, electricity consumption is the main driver of fossil fuel consumption.

The dominant contributors to fossil fuel consumption are the transportation from collection centres to the processing plant and the shredding process, primarily due to electricity consumption by the plant. As for GHG emissions, shredding, particularly as electricity consumption by the plant, constitutes the main factor. The washing, sorting, and drying processes also significantly contribute to GHG emissions. Moreover, the packaging has the lowest GHG emissions among all the production processes.

Table 6
Details of the machines and their characteristics.

Process	Machine manufacturer	Machine model	Throughput (kg/h)	Power (kW)	Ref.
Sorting and washing	Shandong New Haina Machinery Co., Ltd.	GM600+GM250	300	10.50	[41]
Drying	Taizhou Weiss Machinery Co., Ltd.	HG-20	30	0.63	[42]
Shredding	Chaozhou Longhe Plastic Machinery Co., Ltd. Guangzhou Branch	PF400B-1	125	7.50	[43]
Packing	Guangdong Huanlian Intelligent Packaging Group Co., Ltd.	HL-F150	250	1.30	[44]

Table 7
Fuel and electricity consumptions and associated GHG emissions for 1 kg of textile fibre.

Process	Diesel (kL)	Electricity (kWh)	Energy (MJ)	GHG (kg CO_2-e)
Transportation	0.159	-	3.074	0.216
Sorting and washing	-	84.0	0.151	0.035
Drying	-	50.4	0.091	0.021
Shredding	-	150.0	0.270	0.060
Packing	-	13.0	0.023	0.005
Total			3.610	0.338

Table 8
GHG emissions of fibres.

Fibre types	GHG (kg CO_2-e /kg)
Textile waste fibre	0.34
Carbon fibre[49]	14.00
Glass fibre [50]	1.70–2.50
Recycled PP fibre [38]	2.04
Virgin PP fibre [38]	3.50

3.5. Environmental and economic comparisons

Textile waste fibre primarily comprises a composite material with polymer matrix resins like epoxy, polyester, and vinyl esters. This study uses textile waste fibre in concrete to not only enhance compressive strength but also significantly improve concrete's deformation capacity and toughness. Through a review of the literature [38,47,48], other common fibres with similar effects when incorporated into concrete include glass fibre, carbon fibre, and polypropylene (PP) fibre. To provide a clear sustainable perspective on the use of textile waste fibre in concrete, this study compares its life cycle assessment indicators, GHG emissions, with those of the other fibres mentioned above, presented in Table 8. Notably, textile waste fibre exhibits a lower GHG emissions indicator compared to other non-polymer fibres, such as carbon, and glass fibres. Moreover, it far surpasses recycled PP fibre in this sustainability metrics, not to mention its significant advantage over Virgin PP fibre. This emphasises the considerable low-carbon and energy-efficient nature of textile waste fibre, showing its great potential for application in sustainable construction practices.

From a financial perspective, if textile waste is not recycled and mostly ends up in landfills, it not only wastes valuable resources but also poses environmental pollution. Moreover, the disposal of textile waste in landfills incurs operational costs, estimated at AU$101.5 per tonne, based on assumptions of 50% landfilling in urban areas and 50% in rural areas [51]. Transforming textile waste from its previous end-of-life cycle, represented by a burial in landfills, to its next life cycle as a resource in concrete not only reduces the burden on the environment but also turns the cost of disposal into potential economic benefits.

The current cost of recycling 1 tonne of textile waste in Australia is around AU$42 based on the Charitable Recycling Australia report in 2021. Compared to the market prices of other mature fibre products commonly used in concrete, such as glass fibre (AU$476/t), PP fibre (~AU$3000/t), and carbon fibre (~AU$15,000/t) [52], textile waste fibre not only saves on landfill operational costs but also demonstrates a high profit potential after low-cost processing. Therefore, the research and application of textile waste fibre deserve greater attention from both the academic and industrial communities.

4. Conclusions

Utilisation of textile waste in cementitious composites provides benefits in terms of improved sustainability in the construction industry and enhanced circularity for textile waste products while helping to resolve serious environmental issues that are felt globally. The analysis of published literature shows that limited studies are available for post-consumer mixed textile waste. The findings on textile fibres as a replacement for fine aggregates are shown as follows:

1. With the increasing amount of textile fibre inclusion in this investigation, the workability of textile-reinforced concrete is decreased, while tensile strength, compressive strength, and the corresponding strain of the textile-reinforced concrete increase. Textile fibres can enhance the ductility of concrete and increase its energy absorption capacity under external environmental damage.
2. For textile waste recycling, the dominant contributors to energy consumption are the transportation from collection centres to the processing plant and the shredding process. The shredding process significantly contributes to GHG emissions, particularly as electricity consumption by the plant.
3. Textile waste fibre exhibits a lower GHG emissions compared to other non-polymer fibres, such as carbon and glass fibres. It not only saves on avoided landfill operational costs but also demonstrates a high-profit potential after low-cost processing.

The application of textile waste in concrete shows promising results in achieving a more sustainable construction material. Economic feasibility and life cycle cost analysis of textile recycling and integration into concrete should be considered in future research scope. The further research may consider applications in non-structural, façade, or cladding, and insulation in the future.

CRediT authorship contribution statement

Amitha Jayalath: Methodology, Software, Formal analysis, Investigation, Data curation, Visualization, Writing – original draft. **Massoud Sofi:** Supervision, Funding acquisition, Writing – original draft. **Thusitha Ginigaddara:** Software, Data curation, Visualization, Writing – original draft. **Hongxiang Gou:** Methodology, Formal analysis, Investigation, Data curation, Visualization, Writing – original draft. **Priyan Mendis:** Conceptualization, Funding acquisition. **Lu Aye:** Methodology, Validation, Resources, Project administration, Writing – review & editing, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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