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Sustainable Incorporation of Recycled Tire Steel and Textile Fibers as a Hybrid Mix in Concrete

Zeeshan Tariq *, **Ali Bahadori-Jahromi** and **Shah Room**

Civil Engineering Department, School of Computing and Engineering, University of West London, St Mary's Road, Ealing, London W5 5RF, UK; ali.jahromi@uwl.ac.uk (A.B.-J.); shah.room@uwl.ac.uk (S.R.)
* Correspondence: zeeshan.tariq@uwl.ac.uk; Tel.: +44-7496381857

Abstract

Sustainability concerns over the management and handling of the growing volume of waste tires have necessitated the exploration of potential applications for the reuse and recycling of this resource, as they are categorized as hazardous wastes and are typically incinerated through thermal processing or dumped in landfills, resulting in significant environmental issues. The recycled steel and textile fibers from tires can be incorporated in concrete to assist in mitigating this impending environmental calamity, primarily by enhancing the efficacy of concrete. The present study aims to investigate the effect of using recycled tire steel fibers (RTSF) and recycled tire textile fibers (RTTF) in concrete, as economically viable and environmentally friendly alternatives to commercially available fibers. Although literature on the use of recycled fibers in concrete is available, the research is very limited in terms of their hybrid use and with minimal environmental analysis. Consequently, to address the gaps, this research concentrates on the use of RTSF and RTTF as a hybrid mix in concrete with life cycle assessment (LCA) to balance the mechanical performance and environmental sustainability. The experimental work is formulated to suggest an optimum dose of RTSF and RTTF, as a hybrid mix form, to be incorporated in concrete that imparts sufficient strength and workability. The fibers were integrated with dosages of 0.75%, 1%, and 1.25% for RTSF and 0.25%, 0.5%, and 0.75% for RTTF, respectively, by volume in non-hybrid form, while in hybrid form, they were reinforced as four different combinations (1%:0.5%, 0.75%, 0.75%, 0.5%, 0.5%:0.5%, and 0.75%:0.25%) by volume of RTSF and RTTF, respectively. Fresh and hardened properties of concrete were tested according to the ASTM standards. The results showed that concrete with hybrid fibers outperformed the concrete with normal individual fibers in both fresh and hardened states tests. The mechanical strength results showed that the synergistic use of RTSF and RTTF can enhance the strength, toughness, ductility, and crack resistance of the concrete. The hybrid mix H1 comprising 1% RTSF and 0.5% RTTF was ascertained as the optimal mix showing the highest mechanical performance with embodied CO_2 and energy values only slightly higher than the control mix, while offering the significant sustainability benefit of utilizing recycled fibers.

Keywords: sustainability; concrete; recycled tire steel fibers (RTSF); recycled tire textile fibers (RTTF); hybrid fibers; workability; strength

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1. Introduction

The growing number of scrap tires is unavoidable due to the constant evolution of the automobile sector. Given that almost 1.5 billion tires are manufactured annually worldwide, disposing of used tires is considered one of the main issues in waste management [1]. The total accumulation including the new disposals that will be landfilled and/or stockpiled is expected to rise to 5 billion by the year 2030 [2]. Waste tires' disposal in landfills causes ground watercourse and soil contamination by emitting toxic chemicals. The chemical composition of tires makes them extremely resistant to deterioration, which increases the negative environmental effects of inappropriate disposal [3]. It is necessary to identify potential uses for this waste, due to environmental concerns over the handling and disposal of the growing quantity of discarded tires. The byproducts of waste tire recycling consist of various components, including approximately 70% by weight of trimmed rubber, 5–30% by weight of steel fibers and wire, and up to 15% by weight of fluff or textile fibers [4]. Many researchers have been looking into using tire waste products to produce building materials in the past few years.

Concrete has become the most widely used construction material due to its availability, cost-effectiveness, and structural versatility [5]. However, concrete's drawbacks in the form of low tensile strength and brittleness are also evident. Fiber addition to the concrete mixture can increase the tensile strength and lower the chance of brittle failure [6]. Additionally, fibers significantly contribute to concrete's increased toughness. Steel fibers have been used in concrete construction for decades. Steel fibers are used to overcome the inherent brittleness and low tensile strength of concrete by improving the crack-bridging potential and maintaining residual tensile strength after cracking [7,8]. In recent years, the use of recycled tire steel fibers (RTSF), which come from the spent tire, as an alternative to commercially available steel fibers, has gained popularity. Concrete research indicates that an effective way to dispose of used tires is to replace some of the industrial fibers with RTSF, as these fibers enhance the mechanical and durability properties of concrete in the same manner as those made with normal steel fibers [9]. Similarly, in the construction industry, as insulating materials and polymer composites, recycled tire textile fibers (RTTF) have garnered a lot of interest recently as a potential replacement for the widely utilized natural and synthetic reinforcement fibers. Although the contamination of impurities and other materials in RTTF can be up to 60–65%, it is considered an innovative byproduct to be used as reinforcement in concrete to lessen the impact on the environment and determine the ideal value-added product performance/cost ratio [10]. These impurities can be reduced by washing, alkaline treatment, sieving, air separation, or blending techniques. Even without full purification, controlled use or hybridization ensures RTTF remain viable for enhancing toughness and sustainability in concrete. In concrete production, RTTF, when used as fiber reinforcement, proved to be a good alternative to commercially available polypropylene fibers [11].

Recycled fiber reinforcement in concrete offers a range of economic, environmental, and practical benefits, especially in terms of sustainable construction. Replacing industrially produced fibers with RTSF reduces power use and greenhouse gas emissions [12,13]. By maintaining the same mechanical characteristics, the carbon emission factor by the steel fibers from tire waste was 0.4–0.8 CO_2/kg, which was about 22% less than the industrial steel fibers [14]. As these fibers are byproducts from the recycling process of waste tires, they are less expensive than virgin fibers. The price of RTSF is approximately five times less than industrial fibers [15,16]. As far as CO_2 emission is concerned, the global warming potential (GWP) of RTSF is much lower than to the industrial fibers [17]. These advantages have encouraged researchers to use recycled fibers from tires as reinforcement in concrete. These fibers can be tailored for more practical and specific usage in terms of improved mechanical strength, durability, and chemical resistance.

2. Aims and Objectives

This research aims to evaluate the mechanical and environmental attributes of concrete reinforced with RTSF and RTTF and to identify the optimal hybrid mix design that improves the mechanical strength while maintaining sustainable embodied carbon and energy efficiency. The main objectives of this research are as follows:

- To experimentally evaluate and compare the mechanical performance of concrete having hybrid mixes of RTSF and RTTF with control concrete mixes and mixes containing individual RTSF and RTTF.
- To determine the optimal hybrid fiber mix ratio with the highest mechanical performance enhancement while maintaining sustainability.
- To conduct a life cycle assessment to quantify the embodied CO_2 and energy values for all concrete mixes to analyze the environmental impacts.

Research Significance

While RTSF and RTTF have been studied separately, this study is performed to systematically investigate their hybrid use, focusing on the optimal mix ratios, aspect ratio, and performance synergies across compressive, tensile, and flexural strength. The research significance of the synergistic use of RTSF and RTTF lies in their capability to improve the multiscale crack resistance, tensile and flexural strength, load bearing capacity, and the ductility of concrete structures for sustainable infrastructure [18]. Hybrid use can generate synergistic improvements in toughness, ductility, and flexural performance beyond what each fiber achieves alone [11]. Similarly, the hybrid system can delay crack initiation (by RTTF) and resist crack widening (by RTSF), leading to the improved service life of concrete structures. The existing literature only focuses on the use of RTSF or RTTF in their individual capacities without studying their performance in concrete in hybrid form. The current research addresses the gap by identifying the optimal mix design for the hybrid use of RTSF and RTTF in concrete and evaluating mechanical behavior of concrete by conducting compressive, tensile, and flexure assessments of the strength characteristics. This study intends to give future researchers and engineers useful information about the synergistic use of RTSF and RTTF in concrete by growing the present database through these experiments and to promote sustainability. Furthermore, accessing locally available RTSF and RTTF from UK automobile industries is essential to encourage their productive reuse in concrete at the local level. Using locally sourced recycled fibers can support a circular economy, as it can enhance sustainability by cutting waste, lowering costs, creating jobs, support local recycling industries, and ultimately, help to meet environmental regulations. A crucial yet often unexplored dimension in developing sustainable concrete is the quantification of its environmental footprint. With the growing demand for low carbon technologies, assessing the embodied carbon and energy associated with recycled fiber-reinforced concrete is vital. Although RTSF and RTTF improve the mechanical performance of concrete, their processing and integration can influence overall sustainability. This research will therefore also provide an insight into addressing environmental sustainability by incorporating cradle-to-gate LCA to calculate the embodied energy and carbon, offering a comprehensive understanding of the trade-offs between enhanced structural performance and environmental effect.

3. Literature Review

Steel and textile fibers along with other components of scrap tires are considered as hazardous waste and in terms of landfilling or thermal grinding they may lead to several environmental and ecological issues [19]. RTSF have been utilized in past years to reinforce concrete to improve its performance. Different components obtained from waste tire products can be incorporated in making green concrete. Research was carried out by [20] in order to mitigate the negative impact of tire waste removal on the environment by utilizing the rubber crumb and steel fibers obtained from waste tires. The research was based on the replacement of fine aggregates with recycled rubber crumbs, with the addition of recycled steel fibers to enhance shrinkage resistance. The results showed that a 10% replacement of fine aggregates with crumb rubber, with the addition of 1% of steel fibers, increased the compressive and flexural strength of concrete. This also increased the permeability of concrete. However, the permeability of the concrete specimen cured with dry oven conditions, showed a decline. Considering compressive strength as the main outcome, the RTSF were incorporated into soil cement blocks with different ratios of 0%, 0.75%, and 1.5% by volumetric addition. The results showed that with the addition of 1.5% of these fibers increased the compressive strength by 20% [21]; however, this research was limited to the compressive strength. The RTSF were also tested as additions to reinforced concrete columns with different spacings of tie bars to evaluate their confinement and stirrup spaces. The results showed that there was an increase in the compressive strength and ductility of concrete members using a high percentage of steel RTSF [22]. Similarly, RTSF affected the fluidity of the reactive powder concrete (RPC) made by using silica fumes, fly ash, and limestone. However, the mechanical strength was the same as commercially available steel fibers, but these RTSF were more economical [23]. RTSF were also used in self-consolidating concrete to evaluate its mechanical and durability properties. The results suggested a 1.5% volumetric fraction as the optimum percentage of RTSF that had a positive impact on the results of strength and durability [24]. A comparison between the commercially available steel fibers and recycled tire steel fibers in purified and non-purified form with a constant fiber amount of 30 kg/m^3 in concrete mix was studied by the authors of [25]. The use of hybrid mixes of industrial steel fibers and RTSF can enhance the post-crack resistance, elastic modulus, and linear shrinkage of fiber-reinforced concrete in addition to the split tensile and flexural strength [18]. The results revealed better performance in terms of the density, strength, and toughness of purified recycled steel fibers compared to the fibers with rubber and other impurities. The shear performance of reinforced concrete beams incorporated with RTSF (1%, 2%, 3%) was compared with conventionally reinforced concrete beams. The comparison between the analytical and experimental data showed that, with the increase in the content of steel fibers, the shear performance and mechanical strength increased [26]. Furthermore, hybrid models of RTSF were also tested recently. A study [27] suggested the use of a hybrid model containing the RTSF and industrial steel fibers (ISF) to be used as an effective measure for the post-crack response of fiber-reinforced concrete. Similarly, another hybrid model, RHFRC rubberized hybrid fiber-reinforced concrete, was proposed in order to evaluate its compatibility as reinforcement against shrinkage cracks in concrete [28]. By substituting recycled tire fibers for developed fibers, the fiber-reinforced concrete production cost, embodied energy, and embodied carbon were reduced by 13.3% and 68.2%, respectively. For cementitious mortars, in terms of the engineering qualities, cost, and environmental impact, the ideal content of crumb rubber, RTSF, and RTTF was optimized as 5–10%, 1.0 vol%, and 0.5 vol%, respectively [29]. Research also showed the cost comparison of synthetic and recycled steel fibers, and the average cost of industrial steel fibers is more than five times that of recycled steel fibers obtained from waste tires [15]. In addition to the high costs, their manufacturing also involves CO_2 emission. The inclusion of recycled steel fibers from scrap tires enhances the elastic modulus and split tensile strength with reduced linear shrinkage [18]. CMOD (Crack Mouth Opening Deflection) and stress curves associated with the flexural strength of the typical floor concrete showed no deterioration in the mix, but the scattering increased with the increase in the fiber contents [30]. As RTSF has a lower average aspect ratio than industrial fibers, there are fewer fibers in concrete with the same volume fraction, leading to more workable concrete compared to the industrial fibers [31]. The strength and flexural toughness of RTSF-reinforced concrete are inferior to those of industrial steel fiber-reinforced concrete when the fiber volume ratio is the same. The quantity of steel fiber from tires needs to be between 1% and 2% higher than the industrial steel fiber content in order to have the equivalent toughening or strengthening effect [32].

In the past few years, RTTF have attracted interest and are being encouraged to be used as a replacement to the traditional and synthetic reinforcement fibers in construction engineering applications. However, very limited research is available for the use of RTTF in concrete, as textile fibers are considered as discarded products. However, under CER-certified emission reduction code 19.12.08, RTTF are now considered as special wastes and need to be treated properly before disposal [33]. Researchers are working on sustainable reuse of these fibers to offer workable and affordable ways to transform RTTF into a viable and affordable raw material supply [10]. Recent research was conducted for the use of RTTF in the shotcreting technique of normal concrete. The mechanical properties were assessed and showed a positive impact on strength, specifically increasing the deformability and energy absorption capacity of sprayed concrete when reinforced with 1% concentration of RTTF [34]. The dimensions of RTTF are similar to that of industrial polypropylene fibers; so, they can be used as an alternative to these fibers as an economical and sustainable solution. RTTF caused a reduction in the drying shrinkage and increased the durability of concrete, as they have resistance against water and chloride penetration [11]. With the addition of waste tire cord yarn textile fibers in concrete, the co-efficient of thermal conductivity decreased; however, there was a slight reduction in the freeze and thaw resistance [35]. The flexural strength of concrete reinforced with RTTF can be enhanced up to 9.6%, and the fatigue behavior of the concrete is similar to the industrial polypropylene fibers [36]. Apart from concrete, RTTF are used for the stability of expansive soils as an alternative material for industrial fibers. In expansive soils, RTTF can be used as reinforcement materials to improve the strength characteristics and enhance resistance against extensive swelling–shrinkage deformations [37]. RTTF are also helpful in ensuring and enhancing the bearing capacity of sandy soils in terms of strength and ductility parameters; however, in clayey soils, although they increased the ductility and tensile strength, there was a reduction in the compressive and bearing strength of such soils [38].

4. Materials and Methods

A flow chart illustrating various phases of the research work is shown in Figure 1.

Figure 1. Flowchart illustrating the research theme and strategy.

4.1. Materials

Ordinary Portland cement OPC ASTM Type-I [39] Blue Circle general purpose cement from Tarmac Co. (London, UK) was used in this research. The chemical composition of the cement is shown in Table 1.

Table 1. Chemical composition of cement weight (%age).

Oxide	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	Na_2O	K_2O	Others
Content	66.30	21.11	4.91	2.71	1.31	2.40	0.16	0.6	0.5

Two types of natural coarse aggregates with sizes of 20 mm and 10 mm were used in this research, meeting the requirements for 10 mm and 20 mm nominal size fractions. Fine aggregate in the form of natural sand, with a maximum size of 4 mm and below confirming within Zone-II, was considered in this study. The sand was oven dried before usage to remove the moisture. All the materials were sourced from Travis Perkins (London, UK). To maintain workability and keep the slump within the targeted range, SikaMix^R Plus (London, UK) superplasticizer was used with a constant w/c of 0.47 for all the mixes. The quantity of the superplasticizer was kept constant at 0.5% by weight. For mixing and curing the concrete specimens, normal potable water was used.

The recycled fibers including RTSF and RTTF were obtained from Big Atom Company (London, UK). The steel fibers processed from passenger and commercial tires with 5% rubber granules and other impurities were obtained. The impurities were removed by using sieving methods and visual inspection, to retain less than 1% of impurities, as shown in Figure 2.

(**a**) (**b**)

Figure 2. (**a**) RTSF with impurities; (**b**) RTSF after impurity removal.

As the received RTSF had different diameters and lengths, in order to determine the dimension properties of these fibers, the procedure from [31] was adopted. First, 50 g of purified RTSF was weighed, counted, and measured for the length and diameter within different ranges. The thick fibers with a diameter of more than 1 mm were removed before further distribution. The technical properties of RTSF are described in Table 2.

Table 2. Properties of RTSF.

Property	Unit	Results
Density	kg/m^3	7800
Diameter	mm	0.2–0.6
Length	mm	8–25
Tensile Strength	MPa	>2400
Aspect Ratio	n/a	51 ± 5
Elastic Modulus	GPa	180
Shape	n/a	Irregular
Color	n/a	Light Golden

The tire textile fibers recovered from the recycling process had approx. 30% of fine rubber particles, which was reduced to 15% by sieving the fibers and removing approx. 10–15% of the rubber particles, as shown in Figure 3.

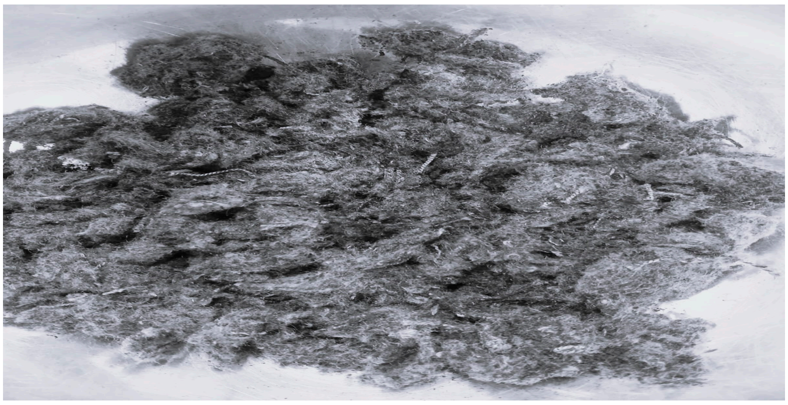

Figure 3. Purified RTTF.

The technical properties of RTTF are shown in Table 3.

Table 3. Properties of RTTF.

Property	Unit	Results
Density	kg/m^3	1180
Length	mm	5 ± 2
Tensile Strength	MPa	>400
Elastic Modulus	GPa	3.5
Chlorine Content	ppm	<33
Color	n/a	Grey

It is important to note that rubber particles adhere to the surface of the fibers, which could somewhat impair the mechanical characteristics of the concrete mix. Rubber particles with size larger than 6 mm are considered oversized contaminants and negatively affect the matrix bonding and fiber dispersion. Similarly, rubber particles with a size smaller than 1 mm can behave like fine rubber powder and affect the consistency of the mix. Although the obtained fibers were quite clean, we removed the residual rubber fragments by sieving the fibers through sieve no. 3 (to remove the particles larger than 6 mm) and sieve no. 16 (to remove the particles smaller than 1.5 mm) on a vibrating table. To ensure uniform fiber geometry and better functionality, the retained percentage was made up of rubber-free fibers with just tiny residual rubber particles in the size range of 1.5–6 mm.

4.2. Mix Proportion

A concrete mix for the characteristic strength of 35 MPa with a targeted slump range of 75–100 mm was designed for this research. All the concrete constituents were tested to check their conformity with the relevant standards. Trial mixes were cast and tested in order to determine the exact quantity of materials to obtain the required strength. To evaluate the effect of superplasticizer, two control mixes, i.e., one without superplasticizer and the other with 0.5% of superplasticizer by weight of cement, were considered. The water–cement ratio was kept at 0.47 for all the mixes. Six mixes, three for RTSF and three for RTTF were prepared with 0.75%, 1%, and 1.25% for RTSF and 0.25%, 0.5%, and 0.75% for RTTF, respectively, by volume. To study the synergistic effect of RTSF and RTTF, four mixes with different fiber volume were made. C1 is the control mix with cement, CA, FA, and water, and C2 is the mix with superplasticizer, S1, S2, and S3 with 0.75%, 1%, and 1.25% V_f of RTSF, whereas T1, T2, and T3 are the mixes with 0.25%, 0.5%, and 0.75% V_f of RTTF. Regarding the hybrid fibers, H1 is the mix with 1% V_f of RTSF and 0.5% V_f of RTTF, H2 has 0.75% V_f of both RTSF and RTTF. Similarly, H3 also has an equal volume of 0.5% of RTSF and RTFS, and H4 has 0.75% V_f of RTSF and 0.25% V_f of RTTF. The details of the mix design for the control and design mixes are shown in Table 4.

Table 4. Mix design details of concrete ingredients.

Mix Design Details										
Mix ID	Cement	Coarse Aggregate		Sand	Water	S.P	RTSF		RTTF	
		20 mm	10 mm				Volume	Amount	Volume	Amount
	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	%	kg/m^3	%	kg/m^3
C1	431.9	422.81	631.84	670.74	203	-	-	-	-	-
C2	431.9	422.81	631.84	670.74	203	2.16	-	-	-	-
S1	431.9	422.81	631.84	670.74	203	2.16	0.75	58.5	-	-
S2	431.9	422.81	631.84	670.74	203	2.16	1	78.0	-	-
S3	431.9	422.81	631.84	670.74	203	2.16	1.25	97.5	-	-
T1	431.9	422.81	631.84	670.74	203	2.16	-	-	0.25	2.9
T2	431.9	422.81	631.84	670.74	203	2.16	-	-	0.5	5.8
T3	431.9	422.81	631.84	670.74	203	2.16	-	-	0.75	8.7
H1	431.9	422.81	631.84	670.74	203	2.16	1	78.0	0.5	5.8
H2	431.9	422.81	631.84	670.74	203	2.16	0.75	58.5	0.75	8.7
H3	431.9	422.81	631.84	670.74	203	2.16	0.5	39.0	0.5	5.8
H4	431.9	422.81	631.84	670.74	203	3.24	0.75	58.5	0.25	2.9

4.3. Casting and Molding

The mixing of concrete was performed as per ASTM C-192 [40]. All of the concrete ingredients were weighed and combined in the precise amounts, as specified in the mix design. The mixing process was performed in a powered concrete mixer. Overall, 50% of the fibers were premixed with the coarse aggregates so that they could be dispersed throughout the mixture during the mixing process. Coarse aggregates and sand were mixed in the mixer until they were the same color. Then, the cement was added to the mix, and the mixer was operated again. Water was added during the mix process in addition to the superplasticizer. The superplasticizer was mixed with 100 mL of water and then added to the mix. The mixer was stopped after 3 min, and to remove the material from the sides, it was tamped with a rubber hammer and then with a trowel. The mixer was again operated for 2–3 min, and the remaining amount of water was added. Concrete was molded after a uniform and consistent mix was achieved. The mixing process was completed within ten to fifteen minutes from the initial mixing. The molds were filled with concrete and left for 24 h as shown in Figure 4.

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Figure 4. Casted set of concrete specimens.

The compositions of the control specimens and the test specimens are presented in Table 4. The molds were oiled and filled in layers with proper tamping and then placed on the vibrator to remove the extra voids from the mix. All the cast molds were left for 24 h drying time at room temperature in the lab. After 24 h, the specimens were removed from the molds as shown in Figure 5 and placed in the curing tank for normal curing, as per ASTM C-192 [40]. Figure 6 shows the curing process of the specimens.

Figure 5. Concrete specimens removed from the molds.

Figure 6. Curing of concrete specimens.

4.4. Tests Performed

The concrete specimens were tested in both fresh and hardened states. Table 5 shows the details and the standards used for the testing.

Table 5. Test standards.

Concrete State	Test Performed	Specimen	Test Standard	Reference
Fresh	Slump	Cone	C-143/C143M	[41]
	Density	Cylinder	C-138/C138M	[42]
Hardened	Density	Cylinder	C-138/C138M	[42]
	Compressive Strength	Cube	BS EN 12390-3	[43]
	Tensile Strength	Cylinder	C-496/C496M	[44]
	Flexural Strength	Beam	C-78/C78M	[45]

Six cubes, 6 cylinders, and 6 beams were cast for each mix to test 3 specimens each at 7 and 28 days. Concrete cube samples, each measuring 100 mm × 100 mm × 100 mm, were used for compressive strength. Similarly, for the split tensile and flexural strength tests, cylinders of 150 mm diameter and beams specimens of 100 mm × 100 mm × 500 mm were prepared, respectively. After 24 hours of casting, the concrete specimens were demolded and placed in a curing tank for water curing. All the strength tests were performed at 7 days and 28 days post-curing.

4.5. Life Cycle Assessment

Over the past several years RTSF and RTTF have attracted interest and are being encouraged to be used as a substitute for traditional and synthetic reinforcement fibers in construction engineering applications. However, the preparation and utilization of such fiber-reinforced concrete can also have an impact on climate change and environmental pollution. One of the main aspects of this research is to assess the actual carbon footprint of making this low carbon concrete with different industrial wastes. Therefore, LCA is used to evaluate the sustainability of the hybrid fiber-reinforced concrete. To assess the impact of the concrete on environmental pollution and climate change, it is vital to focus on the complete manufacturing process, transportation, and placement of concrete as well as the individual components or raw materials used for this process [46,47]. The entire life cycle of concrete is included in the manufacturing process, from the extraction of the raw materials, waste, or recycled materials, and their preparation to the final disposal of the concrete [48]. The lifespan estimation of concrete is made possible by the LCA performed in compliance with the ISO 14044 framework [49,50]. The next step involves developing the Life Cycle Inventory (LCI), which compiles data on resource inputs and emissions associated with the product system, including material usage and embodied carbon values. This is followed by the Life Cycle Impact Assessment (LCIA), where potential environmental effects are quantified and evaluated. Finally, during the Life Cycle Interpretation phase, results from the LCI and LCIA are examined to draw insights and propose strategies for minimizing embodied carbon, particularly within the construction sector [46,51,52].

4.5.1. Functional Unit and System Boundary

The functional unit adopted for this study is 1 m^3 of concrete, which serves as a consistent basis for comparing the environmental impacts of different mix designs. This unit allows for a direct assessment of the embodied carbon and energy across variations in fiber type and dosage, independent of structural dimensions or application. The system boundary follows a cradle-to-gate (A1–A3) approach, encompassing three key stages: (A1) extraction and processing of raw materials, (A2) transportation of constituent materials to the batching facility, and (A3) concrete production and mixing operations. The use phase, maintenance, and end-of-life stages are excluded from this assessment to focus specifically on the production-related impacts. This boundary choice aligns with ISO 14044 and common practice in construction material LCAs, where production stages typically contribute the highest proportion of total embodied emissions.

4.5.2. Life Cycle Inventory

The life cycle inventory (LCI) for this study was developed using a combination of primary and secondary data sources. Material quantities for each mix design were obtained directly from the experimental program, while emission and energy factors for individual constituents—such as cement, aggregates, water, and superplasticizer—were primarily sourced from the Inventory of Carbon and Energy (ICE v3.0) database developed by the University of Bath, UK [53,54]. For recycled tire steel fibers (RTSF) and recycled tire textile fibers (RTTF), the values were derived from the recent peer-reviewed literature and adjusted to reflect local UK production and transportation conditions. Transportation distances were estimated based on typical regional supply chains. All data were converted to a consistent functional unit of 1 m^3 of concrete, ensuring transparency and comparability across the twelve mix designs. Table 6 provides an overview of the energy and embodied carbon components for each material used to make concrete with RTSF and RTTF.

Table 6. Carbon and energy factors.

Ingredient	Embodied Carbon Factor (kg CO_2 e/kg)	Embodied Energy Factor (MJ/kg)
Portland Cement	0.910	4.6
Fine Aggregates	0.005	0.08
Coarse Aggregates 10 mm	0.005	0.08
Coarse Aggregates 20 mm	0.005	0.08
Water	0.00034	0.0014
Superplasticizer	2.4	40
RTSF	0.4	20
RTTF	0.2	15

4.5.3. Life Cycle Impact Assessment (LCIA)

The Life Cycle Impact Assessment (LCIA) phase was conducted to quantify the environmental burdens associated with each mix design. Two key impact categories were considered: embodied carbon (expressed as kg CO_2-equivalent) and embodied energy (expressed as MJ per m^3 of concrete). The embodied carbon for each constituent material was determined by multiplying its quantity by the corresponding emission factor, while embodied energy was calculated using the respective energy intensity values. The total impact per cubic meter of concrete was obtained by aggregating contributions from all materials, transportation, and mixing operations. The assessment was performed using a cradle-to-gate (A1–A3) approach in accordance with ISO 14044 [49] principles, ensuring methodological consistency and comparability. This simplified yet robust method provides a transparent framework for evaluating the trade-offs between mechanical performance improvements and environmental implications of incorporating recycled tire steel and textile fibers into concrete. The following equation was used to determine the embodied carbon for the mix designs [46]:

$$\text{Total Embodied Carbon} \sum_{i=0}^{n} (ECF_i \times Q_i) \quad (1)$$

where n = total number of materials, Q_i = material quantity (kg), $ECFi$ = embodied carbon factor (kg CO_2 e/kg)

5. Results and Discussion

The overall results are shown in Table 7. A summary table showing the 28-day strength variation of all the test mixes with respect to the control mixes C1 and C2 is shown in Table 8.

Table 7. Fresh and hardened concrete test results.

Mix ID	Fresh Concrete			Hardened Concrete					
	Slump (mm)	Density (kg/m^3)		Compressive Strength (MPa)		Split Tensile Strength (MPa)		Flexural Strength (MPa)	
		Fresh	Hardened	7-day	28-day	7-day	28-day	7-day	28-day
C1	85	2347	2306	24.47	36.71	2.96	3.51	3.89	5.01
C2	109	2361	2321	28.24	37.83	3.29	3.78	4.38	5.31
S1	88	2396	2371	28.10	37.85	3.57	4.29	4.81	5.78
S2	81	2409	2381	27.92	37.91	3.81	4.55	5.12	6.07
S3	76	2423	2395	28.48	37.69	4.02	4.71	5.47	6.23
T1	86	2363	2342	27.97	37.45	3.43	3.94	4.59	5.68
T2	82	2362	2347	28.03	37.02	3.58	4.14	4.76	5.91
T3	72	2367	2355	27.91	36.54	3.47	3.97	4.63	5.71
H1	79	2391	2376	29.35	39.19	4.01	4.96	5.63	6.68
H2	76	2376	2359	29.10	38.97	3.73	4.76	5.26	6.29
H3	86	2367	2351	28.21	38.08	3.29	4.17	5.17	6.11
H4	80	2389	2372	28.82	38.87	3.66	4.69	5.35	6.41

Table 8. 28-day strength variations with respect to C1 and C2.

Mix ID	28-Day Compressive Strength			28-Day Split Tensile Strength			28-Day Flexural Strength		
	MPa	Variation with Respect to C1 (%)	Variation with Respect to C2 (%)	MPa	Variation with Respect to C1 (%)	Variation with Respect to C2 (%)	MPa	Variation with Respect to C1 (%)	Variation with Respect to C2 (%)
C1	36.71	0	-	3.51	0	-	5.01	0	-
C2	37.83	-	0	3.78	-	0	5.31	-	0
S1	37.85	3.11	0.05	4.29	22.22	13.49	5.78	15.37	8.85
S2	37.91	3.27	0.21	4.55	29.63	20.37	6.07	21.16	14.31
S3	37.69	2.67	−0.37	4.71	34.19	24.60	6.23	24.35	17.33
T1	37.45	2.02	−1.00	3.94	12.25	4.23	5.68	13.37	6.97
T2	37.02	0.84	−2.14	4.14	17.95	9.52	5.91	17.96	11.30
T3	36.54	−0.46	−3.41	3.97	13.11	5.03	5.71	13.97	7.53
H1	39.19	6.76	3.60	4.96	41.31	31.22	6.68	33.33	25.80
H2	38.97	6.16	3.01	4.76	35.61	25.93	6.29	25.55	18.46
H3	38.08	3.73	0.66	4.17	18.80	10.32	6.11	21.96	15.07
H4	38.87	5.88	2.75	4.69	33.62	24.07	6.41	27.94	20.72

5.1. Workability

As it was obvious that the induction of fibers will decrease the workability of the concrete, another control mix was prepared by using superplasticizer without disturbing the mix design of the original control mix. A mix was prepared without superplasticizer and using 1.25% of the RTSF as trial to evaluate the effect of the fibers on the concrete mix design. The slump test showed a significant decrease in workability due to the balling effect caused by the fibers clumping, as studied by [55], and the slump was reduced to below 20 mm as shown in Figure 8. The clumping was attributed to the balling effect of the fibers, which instead of dispersing uniformly formed bundles and increased the internal friction in the concrete mix. With the same amount of water as that of control mix, reduced flow was observed and caused a honey combing effect in the fresh concrete. Figure 8 illustrates the balling effect encountered during the trial mixes, where the fibers tended to cluster rather than dispersing uniformly within the mix. It is worth noting that this preliminary test was carried out solely as an initial assessment for fiber incorporation and is not included in the final mix design matrix. So, in order to make the mix workable, superplasticizer was used not to decrease the amount of water but to maintain the targeted slump.

The workability of fresh concrete was assessed, according to the ASTM C-143 standard [41]. The results for the slump tests are shown in Figure 7.

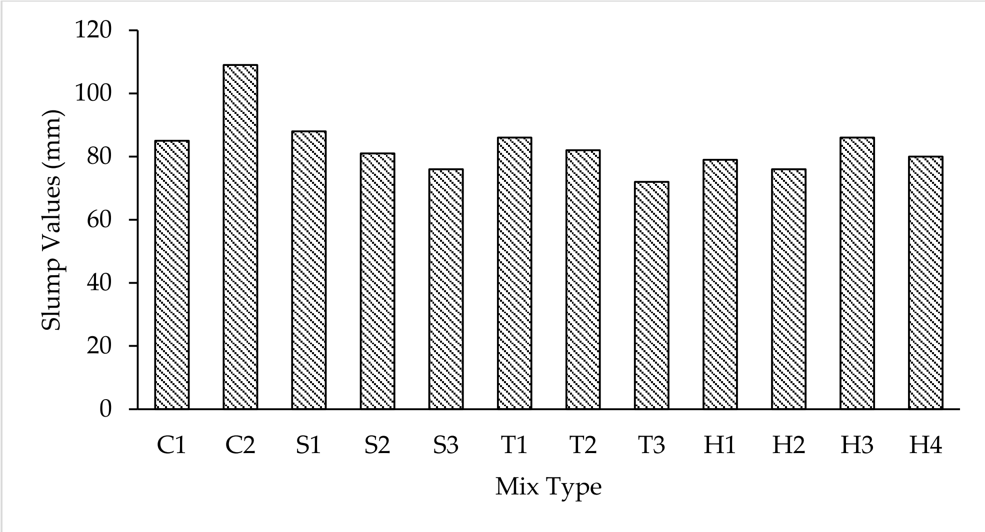

Figure 7. Slump test results.

Figure 8. Reduction in slump due to balling effect.

The slump was increased by 28.2% in C2 by using 0.5% superplasticizer by weight of cement compared to C1. For RTSF, the workability was decreased with an increase in the fibers content as compared to the C2, but the values of all the mixes remained within the design slump limit as of C1 except for the mix T3. The results were in accordance with the studies performed by [18,30,56,57]. The decrease in the workability of all the test mixes was attributed to the small diameter, irregular shape, and high aspect ratio of the RTSF. The same pattern was observed in case of RTTF, where the decrease in workability was found to be increasingly noticeable as the RTTF content increased. These results were consistent with the previous research studies [11,58,59]. The decrease in flowability of all the test mixes was attributed to the fibers and minor impurities in the form of rubber granules that absorbed the water and made the mixture viscous. Although, for the mix T3, the slump value of 72 mm was slightly below the targeted range of 75–100 mm, this minor deviation is within the acceptable tolerance for practical applications, and a modest admixture adjustment could be employed in practice to achieve full compliance. The hybrid fibers mix followed the same trend. The flowability of the concrete decreased with the induction of hybrid fibers; however, with the use of the superplasticizer, the targeted slump was achieved in all hybrid mixes. The flowability was decreased by about 26.7% to 37.9% as compared to the C2 control mix. The maximum slump was achieved by the H3 mix, which was 26.7% less than the C2 mix. The mixes with 1.5% addition of fibers decreased more workability than the mixes with 1% hybrid fibers. Similarly, the hybrid mix with more RTSF had less workability, due to their irregular shape and size. It was observed that all the concrete mixes with hybrid RTSF and RTTF were homogenous and cohesive. This homogeneity was attributed to the use of refining the fibers after removing the rubber and other impurities. Overall, the hybrid mixes with a relatively low volume fraction of RTTF were more workable.

5.2. Density of Concrete

The density of concrete was assessed according to the ASTM C138 standard (Density, Yield, and Air Content of Concrete) [42]. The results for the density tests are shown in Figure 9.

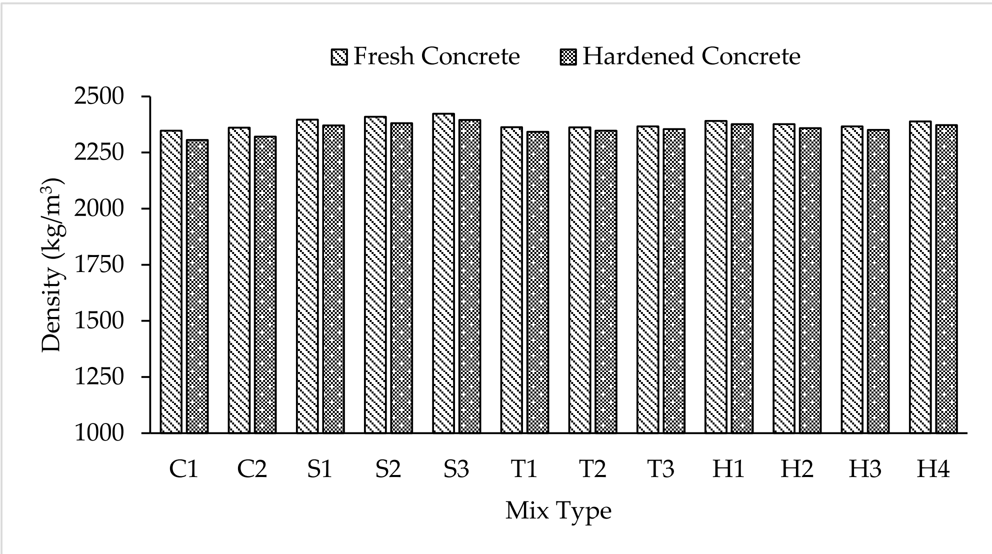

Figure 9. Densities of fresh and hardened concrete mixes.

The density of fiber-reinforced concrete is affected by different factors, including the individual densities of the aggregates, voids ratio, amount of cement, and water content of the mix design. The results obtained followed the general trend that the fresh density of concrete was slightly higher than the hardened concrete, which was also illustrated in [60]. The controlled specimen C2 had higher fresh and hardened densities than C1 because of the use of superplasticizer; however, this increase was slightly too mild, as there was no reduction in the water content of the mix C2 and more solid particles per volume of the mix. The results showed a very moderate variation in the densities of the mixes with RTSF, and there was an increase in the fresh and hardened densities with an increase in the fiber contents, due to the high unit weight of RTSF. This trend, as shown in Figure 9, was the same pattern as studied by [61]. However, in terms of the variation across the fresh and hardened concrete for RTSF mixes, there was slight reduction in the hardened densities as compared to the control specimen. This was because of the ability of the RTSF to bridge the crack formation process and limit the void formation. For the mixes with RTTF, the fresh densities were very close to the control mix C2, and there was very slight variation in these values even with the increase in the fiber content. Because RTTF are a light and low-density material, they can somewhat lower the fresh density by adopting a less dense substance for a portion of the mix. However, for the hardened densities, there was an increase as compared to C2 because of the crack resistance and stress distribution mechanism of the RTTF, and a slight reduction from the fresh densities was observed. The same results were obtained in the experimental work of [34,62]. The higher the contents of individual RTSF and RTTF, the higher the porosity and water absorption, as workability issues can slightly increase the air voids [63,64]. For the hybrid mixes, the fresh and hardened densities were higher than the controlled mix. The maximum density was observed in the case of the H1 mix because of the higher content of RTSF. An increase of 1.5% to 2.8% in the densities of hardened concrete mix was observed. The increase was attributed more to the presence of RTSF but limited to the control mix C2. However, the presence of RTTF reduced the densities of the hybrid mix as compared to the mixes containing only RTSF. The decline in the hardened densities was observed and was attributed more to the presence of RTTF because of their lower unit weight as compared to the other concrete components. Similarly, the higher air entrainment and voids because of rough surface area of RTTF also contributed to this decrease. The overall range of the fresh and hardened densities of all the mixes was between 2300 kg/m^3 and 2420 kg/m^3, which was as per the standards. As far as RTSF are concerned, the resistance in the movement of concrete particles caused air voids in the hardened concrete and ultimately decreased the hardened densities. In comparison to ordinary concrete, the hybrid fiber concrete exhibits a lower overall density decrease from the fresh to the hardened condition. To keep fresh concrete workable and from becoming overly heavy or porous, hybrid fibers balance one another and improve the overall mechanical efficiency by ensuring lower porosity, a more stable hardened density, and better long-term integrity.

5.3. Compressive Strength of Concrete

The compressive strength of the concrete was assessed according to the BS EN 12390-3 standard (the compressive strength of test specimens of hardened concrete, which can be cubes or other prescribed geometries) [43]. Figures 10 and 11 show the arrangement and the results for the compressive tests.

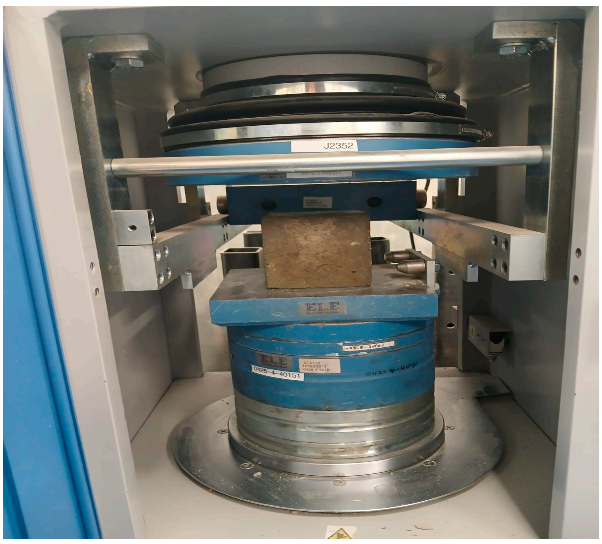

Figure 10. Compressive strength test arrangement.

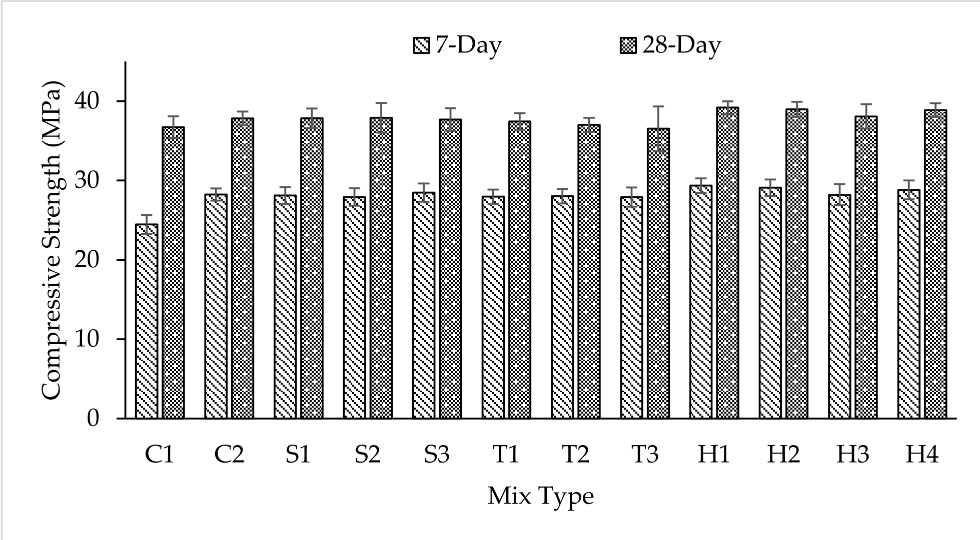

Figure 11. Compressive strength test results.

The compressive strength of the normal concrete C1 after 28 days was 36.71 MPa compared to the control specimen C2, which had 37.83 MPa. The compressive strength result showed a 15.4% increase in C2 as compared to the C1 at the 7-day testing. The same increase was observed at the 28-day testing, but the increase was limited to 3.05% as compared to the C1 at the 28-day test results. This was attributed to the use of the high early strength superplasticizer in C2 mix. The effects of RTSF on the compressive strength of concrete are generally less pronounced compared to their effects on the tensile or flexural strength. The test results showed a very slight increase of 0.2% with the increase in the fiber volume from 0.75 to 1%. However, at a 1.25% volume replacement, the CS was slightly decreased by 0.38% as compared to the C2 mix. The results of the CS test were aligned and were well correlated with the available literature data [28,62,65–67]. On the other hand, some studies suggested that steel fibers can increase the compressive strength up to an optimum amount of dosage [22,25,57]; however, this increase was attributed to the concrete type, the ratio of the fiber length to maximum aggregate size, the volume ratio between long and short fibers, the size, shape, aspect ratio, volume fraction, orientation, and surface characteristics of the fibers, which can all affect compressive strength [68]. For RTTF, a continued slight decrease in compressive strength with the increase in the fiber content was observed. The compressive strength was decreased by 3.5% with 0.5% RTTF by volume fraction. However, as a whole, RTTF just caused slight variations in compressive strength, and the observed decrease as compared to the RTSF was due to the presence of 2% of rubber particles that caused a slightly lower quality of hydration paste. The trend followed the same pattern as observed in the studies of [35,36,58,59]. The strength of the mix T3 was close to the control mix C1, which was less than the mix C2. The overall range of the compressive strength result with RTTF was satisfactory, as it remained close to the control mix, because the RTTF were inducted only up to 0.75% of the volume fraction. Above this level, the trend of decrease in the compressive strength was moderate because of the decrease bonding capacity and increased porosity of the mixes with a higher volume of RTTF, due to the increase in the surface area. For individual fiber reinforcement, the maximum compressive strength of 37.91 MPa was observed in the S2 mix with 1% of RTSF, and the minimum strength of 36.54 MPa was observed for the T3 sample with 0.75% RTTF. For the hybrid mixes, the compressive strength was increased by 0.7% to 3.5% as compared to the control specimen C2. All the hybrid samples had higher strength than the samples with individual fibers. The maximum strength of 39.19 MPa was observed in H1 sample with a hybrid mix of 1% RTSF and 0.5% RTTF. The results indicated that the hybrid mix H1 had the maximum gain of 6.76% and 3.60% in compressive strength with respect to the C1 and C2 mixes, respectively. The trend across the samples showed that the hybrid samples a with higher level of RTSF and a lower level of RTTF had higher compressive strength. This was attributed to the bridging mechanism and adequate material bonding to avoid microcracking formed by the combination of hybrid fibers. One of the important behaviors observed during the testing was the enhancement in the concrete ductility in all of the hybrid specimens. Normal concrete failed abruptly with violent explosive failure behavior, while the concrete with fibers had a more ductile failure, as shown in Figure 12. The compressive strength result showed that the combination of RTSF and RTTF can enhance the strength, toughness, ductility, and crack resistance of the concrete.

Figure 12. Ductile failure of hybrid mix concrete.

5.4. Split Tensile Strength of Concrete

The split tensile strength was assessed according to the ASTM C496 standard (Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens) [44]. Figures 13 and 14 show the test arrangement and the results for the tensile strength test.

Figure 13. Split tensile strength test arrangement.

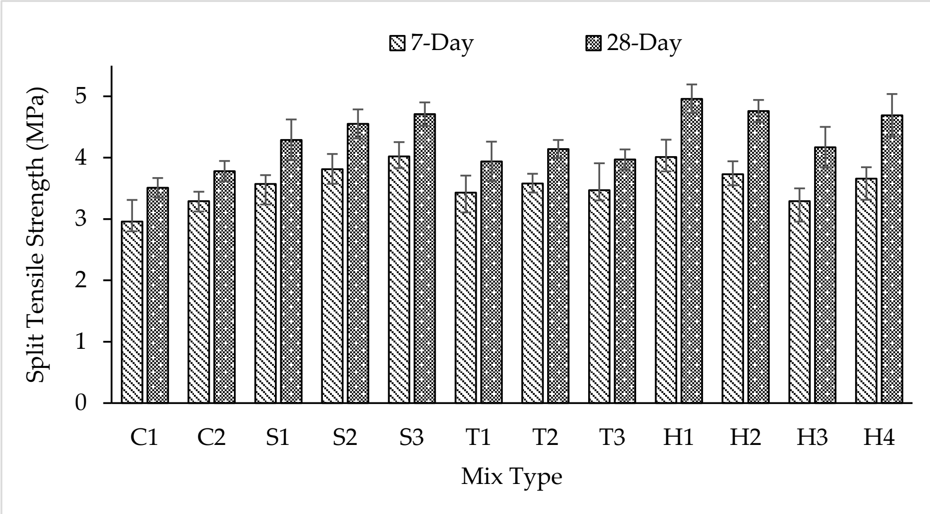

Figure 14. Split tensile strength test results.

The split tensile strength of the controlled mixes C1 and C2 were 3.51 MPa and 3.78 MPa, respectively. The mix with superplasticizer had 7.5% more strength than C1. In terms of the RTSF, the split tensile strength increased with the increase in the fiber volume. The maximum strength of 4.91 MPa was observed at 1.25% of RTSF, which was 24% more than the control mix. The enhancement is caused by the steel fibers' higher stiffness and strength in comparison to the cement paste. The steel fibers improve the concrete's elastic modulus under tension, maintaining a high-tension force. However, it was observed that there was decline in the trend of increasing strength from 1% RTSF to 1.25% RTSF, with a 3.5% increase in strength from S2 to S3 as compared to a 6% increase from S1 to S2. This was attributed to the entrapped air and voids caused by the high volume of RTSF that caused poor dispersion and a knotting effect in the mix. The findings were in accordance with the studies performed by [18,30,31]. The same trend was followed in the case of RTTF in the concrete mixes, as the strength increased from 4.2% to 9.5% as compared to the concrete mix C2. The maximum tensile strength of 4.14 MPa was observed for the mix with 0.5% of RTTF. There was an initial increase in strength with the increase in the fiber volume, and concrete behaves differently with RTTF added, enabling the samples to sustain detectable post-break loads and undergo notable deformation even when they shatter. This increase in strength was because of the rough surface of RTSF that may have a satisfactory bonding capacity to the cement paste. Another possible explanation for this enhancement in performance is that the flexibility of RTSF raises the friction across the fiber and the cement paste around it, increasing the resistance to the tension force. However, at a 0.75% fiber volume of RTTF, the split tensile strength was decreased as compared to the sample with 0.5% of RTTF but still more than the control mix C2. The same results regarding the split tensile strength of RTTF were obtained during the research studies of [34]. For the hybrid mixes, all the samples had more strength as compared to the control specimens and the mixes with individual RTTF as shown in Figure 14. Mix H1 had the highest tensile strength of 4.96 MPa of all the mixes, which was 31% more than the control mix and even 5.5% more strength enhancement than the S3 mix. It was observed that the hybrid samples with a larger amount of RTSF had more influence on the split tensile strength. The synergistic effect of RTSF and RTTF provides the toughness and increased tensile capacity more than using these fibers alone. This increase in strength was attributed to the stiffness and high modulus of RTSF that contributed towards bridging wider cracks and the carrying load after initial cracks. Similarly, the addition of RTTF in this hybrid mixes controlled the micro cracks and reduced the crack spacing, retarding the crack propagation up to a certain load and ultimately increasing the toughness of the member. However, it was observed in the case of the H2 mix with a 0.75% volume fraction of each of the RTSF and RTTF that the strength was lower than the other samples. This was due to the high dosage of RTTF that caused air voids and a tangling effect of fibers within the mix. The results indicated that the hybrid mix H1 had the maximum gain in tensile strength of 41.31% and 31.22% with respect to the C1 and C2 control mixes, respectively. Overall, the results showed that the synergistic use of these fibers can provide moderate volume and better rheology control to enhance the tensile strength of the fiber-reinforced concrete.

5.5. Flexural Strength of Concrete

The flexural strength was assessed according to the ASTM C78 standard (Third-Point Loading Test on Beams) [45]. Figures 15 and 16 describes the test arrangement and the results for the flexural strength test.

Figure 15. Flexural strength test arrangement.

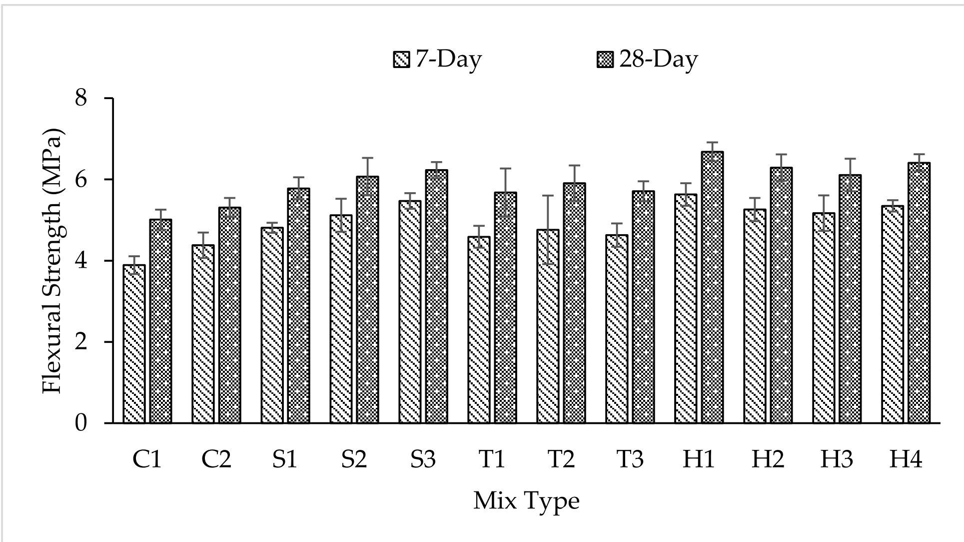

Figure 16. Flexural strength test results.

The flexural strength results followed the same trend as that of the split tensile strength. The strength was increased with the increase in the fiber volume of the RTSF individually. There was an increase of 9% to 17.5% of strength as compared to sample C2. The maximum strength of 6.23 MPa was observed in the sample with 1.25% RTSF. The results followed the pattern of the previous research [28,31,59,69]. The concrete fracture energy is improved by the fiber pull-out strength, which is influenced by the bonding strength and friction resistance between RTSF and the cement matrix. The trend results showed a decrease in the increment after a 1% level of reinforcement because of the poor dispersion and tangling effect of RTSF as the dose became higher. For RTTF, the maximum flexural strength of 5.91 MPa was observed for the T2 mix with 0.5% RTTF. It was observed that, above this level, the strength was reduced but still higher than the control mix. This was attributed to the capacity of the RTTF to deform significantly before failing, which allows the fiber-reinforced samples to demonstrate a high capacity for plastic energy absorption. The findings followed the experimental works of previous research [4,35,36,58]. The hybrid mixes had more flexural strength as compared to the control and the mixes with RTSF and RTTF in individual forms. The maximum strength of 6.68 MPa was observed in the H1 sample, which was 26% higher than the control mix. Similarly, the hybrid mixes had 7% and 17.6% more strength than the mixes with RTSF and RTTF, respectively. The results indicated that the hybrid mix H1 had the maximum gain in flexural strength of 33.33% and 25.80% with respect to the C1 and C2 control mixes, respectively. The increase in the strength was attributed to the synergistic use of fibers in which RTSF controlled larger cracks and carried the tensile stresses, whereas RTTF handled the microcracks and their propagation at the early age of loading, ultimately leading to better crack control, improved stress distribution, and high strength. It was noted that a higher amount of RTSF increased the strength more than a lower amount of RTSF and equal ratios of RTSF and RTTF. Similarly, higher levels of RTSF also decreased the trend of increasing strength because a high amount of RTSF could have fewer bridging effects, due to the lower average aspect ratio. One of the important points to be remembered while analyzing the flexural strength result is not only the peak load at failure but also the actual behavior of the material during the load application and cracking. The hybrid mixes were observed to provide a failure with cracks that were smaller in width, and the mixes maintained their load carrying capacity for a longer time before failure.

5.6. Environmental Impact Assessment

The embodied carbon and energy for all the mixes of concrete are shown in Figure 17. The results showed that, for the individual fibers, the embodied carbon and energy increased with the increase in the fiber amount as compared to the control specimen. There was an increase of 9.5% and 88.17% in embodied carbon and energy for the S3 sample as compared to the C2. For the RTTF, the values remained close to the control specimen C2. This was attributed to the lower concentration of RTTF by volume in the concrete mix. For the hybrid fiber mixes, the H3 sample showed less carbon and energy as compared to all three samples of the individual RTSF. The maximum amount of carbon and energy was observed in the H1 sample with 440.56 kg of carbon and 3858.45 MJ for energy. However, this was 1.5% and 7.2% less than the highest value of S3 of all the mixes. The results also indicated that hybrid fiber mixes use less energy and embodied carbon as compared to the mixes with individual use of RTSF. These results imply that, although hybrid fibers increase the concrete's environmental impact, it was lower than that of the RTSF and its embedded elements, which are more energy intensive.

The hybrid incorporation of RTSF and RTTF reduced the embodied carbon footprints and energy primarily through material replacement and performance improvement. Since these fibers are the products of the tire recycling process, they have lower carbon and energy compared to the production of synthetic fibers, which require proper resource extraction, transportation, and manufacturing processes. Their reuse diverts waste from landfills and offsets the need for new raw materials, supporting circular economic principles and further decreasing their environmental impact. The LCA results showed that the hybrid fiber mixes not only valorized waste materials but also helped to achieve overall energy efficiency and carbon reduction.

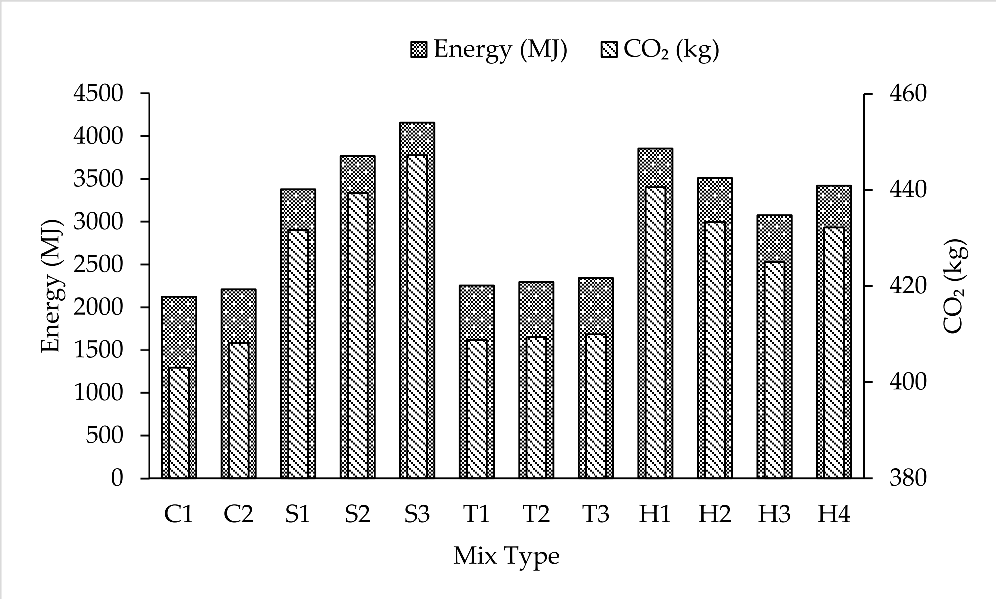

Figure 17. Total embodied carbon and energy.

6. Conclusions

The present research work involved the incorporation of RTSF and RTTF as hybrid mixes for the enhancement of the strength characteristics of fiber-reinforced concrete. Based on the experimental work, the following conclusions have been drawn:

1. The slump decreased with the increase in the fiber content individually and in hybrid form. RTTF had more effect on the reduction in the workability. Similarly, the hybrid fibers also decreased the workability. There was an overall 40% decrease in the slump value as compared to the control specimen. The workability decreased with an increased in the volume of fibers. For the hybrid mix, the maximum decrease in workability was observed in the H2 mix. However, with the use of a superplasticizer, the workability can be maintained within the designed slump limit of the concrete mix.
2. The RTSF increased the fresh density due to their high unit weight, whereas the RTTF decreased the density due to their low bulk density. In hybrid mixes, these effects partially offset one another, resulting in a slight reduction of 0.6% from the fresh to hardened density—less than the 1.6% reduction observed in the control specimen.
3. The compressive strength of hybrid fibers is higher than the mixes with individual RTSF and RTTF. The hybrid fiber mix H1 with 1% RTSF and 0.5% RTTF by volume exhibited a maximum compressive strength of 39.19 MPa, which is 3.5% more than the control specimen and 3.3% and 4.6% more than the individual RTSF and RTTF, respectively. With the induction of hybrid fibers, the ductility and toughness of the concrete is increased.
4. The split tensile strength was increased by 10% to 31%, as compared to the controlled specimen. The maximum strength of 4.79 MPa was obtained for the hybrid mix H1 with 1% RTSF and 0.5% RTTF. The RTSF have more of an effect on the split tensile strength compared to the RTTF. The synergistic use of fibers with a moderate total volume and good rheology in the concrete mix also enhanced the toughness and fracture control over either fiber alone. RTTF delay the onset of splitting cracks, while RTSF control post-crack propagation and widening. Their combined action

resulted in a higher peak split tensile strength and improved ductility compared to the single-fiber mixes.

5. The flexural strength of the hybrid mix was improved by 26%, 7%, and 17.6% compared to the control mix and RTSF and RTTF alone, respectively. The maximum strength of 6.68 MPa was observed in the H1 mix with 1% RTSF and 0.5% RTTF. The fiber matrix interlock prevents weak zones of cracking that can occur with the use of only one type of fiber. The hybrid use of RTSF and RTTF promoted ductile flexural behavior by combining early micro-crack control with strong macro-crack bridging. This synergy increased the toughness, energy absorption, and post-cracking strength, leading to a more gradual and safer failure mode compared to the brittle fracture in plain or single-fiber concrete.
6. The LCA calculations showed that the embodied energy and carbon increased with the increase in RTSF but remained close to control mix for the RTTF. The hybrid incorporation of RTSF and RTTF reduced the embodied carbon footprints and energy primarily through material replacement and performance improvement. There was an increase of 4–8% embodied carbon for hybrid mixes compared to the control mixes and individual RTTF, but it was 5% less than the individual use of RTSF. The hybrid use of recycled tire steel and textile fibers reduces the embodied energy and carbon of concrete by replacing virgin fiber materials with low-impact recycled alternatives. Their reuse diverts waste from landfills and enables improved mechanical performance, allowing material optimization and lower cement demand. This synergistic approach supports circular economic principles while enhancing the sustainability of concrete production.

Overall, this study provides new evidence that the hybridization of RTSF and RTTF yields superior mechanical performance, energy efficiency, and carbon reduction compared to their individual incorporation, thereby addressing the identified research gap and contributing towards sustainable fiber-reinforced concrete solutions.

7. Future Recommendations

For future developments for the use of RTSF and RTTF as a hybrid mix in concrete, the next step should be focused on the durability characteristics of this hybrid fiber-reinforced concrete. Similarly, tests like CMOD (crack mouth opening deflection) can be used to analyze the crack propagation and flexural fatigue behavior during load application.

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References

1. Ting, M.B.; Fakir, S.; Gulati, B.; Haysom, S.; Mytelka, L.L.; Msimang, V.; Mujakachi, L.K.; Muzenda, E.; Perrot, R.; Scholtz, L.; et al. *Earth, Wind and Fire: Unpacking the Political, Economic and Security Implications of Discourse on the Green Economy*; Mytelka, L.K., Msimang, V., Perrot, R., Eds.; MISTRA—Mapungubwe Institute for Strategic Reflection: Johannesburg, South Africa, 2015; p. 340.
2. Valentini, F.; Pegoretti, A. End-of-life options of tyres. A review. *Adv. Ind. Eng. Polym. Res.* **2022**, *5*, 203–213. [CrossRef]
3. Rogachuk, B.E.; Okolie, J.A. Waste tires based biorefinery for biofuels and value-added materials production. *Chem. Eng. J. Adv.* **2023**, *14*, 100476. [CrossRef]
4. Grammelis, P.; Margaritis, N.; Dallas, P.; Rakopoulos, D.; Mavrias, G. A Review on Management of End of Life Tires (ELTs) and Alternative Uses of Textile Fibers. *Energies* **2021**, *14*, 571. [CrossRef]
5. Nilimaa, J. Smart materials and technologies for sustainable concrete construction. *Dev. Built Environ.* **2023**, *15*, 100177. [CrossRef]
6. Ahmad, I.; Ahmad, F.; Room, S.; Abdullah, Z.; Ihsan, M. Compressive Strength of Cement Mortar blended with Coconut Fibers and Human Hair. *Adv. Sci. Technol. Eng. Syst. J.* **2016**, *1*, 1–4. [CrossRef]
7. Halvax, K.; Lublóy, É. Investigation of steel fibers bond strength in mortar matrix. *Pollack Period.* **2013**, *8*, 101–110. [CrossRef]
8. Salam, A.; Room, S.; Iqbal, S.; Mahmood, K.; Iqbal, Q. An experimental study of bond behavior of micro steel fibers added self-compacting concrete with steel reinforcement. *Period. Polytech. Civ. Eng.* **2020**, *64*, 1144–1152. [CrossRef]
9. Golpasand, G.B.; Farzam, M.; Shishvan, S.S. Behavior of recycled steel fiber reinforced concrete under uniaxial cyclic compression and biaxial tests. *Constr. Build. Mater.* **2020**, *263*, 120664. [CrossRef]
10. Fazli, A.; Rodrigue, D. Sustainable Reuse of Waste Tire Textile Fibers (WTTF) as Reinforcements. *Polymers* **2022**, *14*, 3933. [CrossRef]
11. Serdar, M.; Baricevic, A.; Lakusic, S.; Bjegovic, D. Special purpose concrete products from waste tyre recyclates. *Građevinar* **2013**, *65*, 793–801. [CrossRef]
12. Pawelska-Mazur, M.; Kaszynska, M. Mechanical Performance and Environmental Assessment of Sustainable Concrete Reinforced with Recycled End-of-Life Tyre Fibres. *Materials* **2021**, *14*, 256. [CrossRef]
13. Isa, M.N.; Pilakoutas, K.; Guadagnini, M.; Angelakopoulos, H. Mechanical performance of affordable and eco-efficient ultra-high performance concrete (UHPC) containing recycled tyre steel fibres. *Constr. Build. Mater.* **2020**, *255*, 119272. [CrossRef]
14. Biswas, W.K.; Zhang, X.; Matters, C.; Maboud, M. Techno-Eco-Efficiency Assessment of Using Recycled Steel Fibre in Concrete. *Sustainability* **2024**, *16*, 3717. [CrossRef]
15. Qin, X.; Kaewunruen, S. Environment-friendly recycled steel fibre reinforced concrete. *Constr. Build. Mater.* **2022**, *327*, 126967. [CrossRef]
16. Mastali, M.; Dalvand, A.; Sattarifard, A.R.; Illikainen, M. Development of eco-efficient and cost-effective reinforced self-consolidation concretes with hybrid industrial/recycled steel fibers. *Constr. Build. Mater.* **2018**, *166*, 214–226. [CrossRef]
17. Hajimohammadi, A.; Ngo, T.; Mendis, P.; Nguyen, T.; Kashani, A.; van Deventer, J.S.J. Pore characteristics in one-part mix geopolymers foamed by H_2O_2: The impact of mix design. *Mater. Des.* **2017**, *130*, 381–391. [CrossRef]
18. Zia, A.; Zhang, P.; Holly, I. Long-term performance of concrete reinforced with scrap tire steel fibers in hybrid and non-hybrid forms: Experimental behavior and practical applications. *Constr. Build. Mater.* **2023**, *409*, 134011. [CrossRef]
19. Mmereki, D.; Machola, B.; Mokokwe, K. Status of waste tires and management practice in Botswana. *J. Air Waste Manag. Assoc.* **2019**, *69*, 1230–1246. [CrossRef]
20. Shaaban, I.G.; Rizzuto, J.P.; El-Nemr, A.; Bohan, L.; Ahmed, H.; Tindyebwa, H. Mechanical Properties and Air Permeability of Concrete Containing Waste Tires Extracts. *J. Mater. Civ. Eng.* **2021**, *33*, 04020472. [CrossRef]
21. Rocha, J.H.A.; Galarza, F.P.; Chileno, N.G.C.; Rosas, M.H.; Peñaranda, S.P.; Diaz, L.L.; Abasto, R.P. Compressive Strength Assessment of Soil–Cement Blocks Incorporated with Waste Tire Steel Fiber. *Materials* **2022**, *15*, 1777. [CrossRef]
22. Ahmad, I.; Iqbal, M.; Abbas, A.; Badrashi, Y.I.; Jamal, A.; Ullah, S.; Yosri, A.M.; Hamad, M. Enhancement of Confinement in Scaled RC Columns using Steel Fibers Extracted from Scrap Tyres. *Materials* **2022**, *15*, 3219. [CrossRef] [PubMed]
23. Xu, X.; Chen, Q.; Yu, B.; Liu, Q.; Zhang, R.; Liu, Y. Preparation of low-cost reactive powder concrete using waste steel fibres recycled from scrap tires. *Road Mater. Pavement Des.* **2023**, *24*, 1254–1272. [CrossRef]
24. Simalti, A.; Singh, A.P. Comparative study on performance of manufactured steel fiber and shredded tire recycled steel fiber reinforced self-consolidating concrete. *Constr. Build. Mater.* **2021**, *266*, 121102. [CrossRef]
25. Senesavath, S.; Salem, A.; Kashkash, S.; Zehra, B.; Orban, Z. The effect of recycled tyre steel fibers on the properties of concrete. *Pollack Period.* **2022**, *17*, 43–49. [CrossRef]
26. Aksoylu, C.; Özkılıç, Y.O.; Hadzima-Nyarko, M.; Işık, E.; Arslan, M.H. Investigation on Improvement in Shear Performance of Reinforced-Concrete Beams Produced with Recycled Steel Wires from Waste Tires. *Sustainability* **2022**, *14*, 13360. [CrossRef]
27. Vistos, L.; Galladini, D.; Xargay, H.; Caggiano, A.; Folino, P.; Martinelli, E. *Hybrid Industrial/Recycled SFRC: Experimental Analysis and Design*; di Prisco, M., Menegotto, M., Eds.; Springer International Publishing: Cham, Switzerland, 2018; pp. 98–112.
28. Bjegovic, D.; Baricevic, A.; Lakusic, S.; Damjanovic, D.; Duvnjak, I. Positive interaction of industrial and recycled steel fibres in fibre reinforced concrete. *J. Civ. Eng. Manag.* **2013**, *19*, S50–S60. [CrossRef]

29. Chen, M.; Zhong, H.; Chen, L.; Zhang, Y.; Zhang, M. Engineering properties and sustainability assessment of recycled fibre reinforced rubberised cementitious composite. *J. Clean. Prod.* **2021**, *278*, 123996. [CrossRef]
30. Pająk, M. Concrete reinforced with various amounts of steel fibers reclaimed from end-of-life tires. *MATEC Web Conf.* **2019**, *262*, 6008. [CrossRef]
31. Su, P.; Li, M.; Dai, Q.; Wang, J. Mechanical and durability performance of concrete with recycled tire steel fibers. *Constr. Build. Mater.* **2023**, *394*, 132287. [CrossRef]
32. Zhang, Y.; Gao, L. Influence of Tire-Recycled Steel Fibers on Strength and Flexural Behavior of Reinforced Concrete. *Adv. Mater. Sci. Eng.* **2020**, *2020*, 6363105. [CrossRef]
33. Landi, D.; Vitali, S.; Germani, M. Environmental Analysis of Different End of Life Scenarios of Tires Textile Fibers. *Procedia CIRP* **2016**, *48*, 508–513. [CrossRef]
34. Khosh, B.; Atapour, H. Assessment of mechanical behavior of sprayed concrete reinforced with waste tire textile fibers. *Sci. Rep.* **2024**, *14*, 8873. [CrossRef] [PubMed]
35. Malaiskiene, J.; Nagrockiene, D.; Skripkiunas, G. Possibilities to use textile cord waste from used tires for concrete. *J. Environ. Eng. Landsc. Manag.* **2015**, *23*, 183–191. [CrossRef]
36. Chen, M.; Zhong, H.; Zhang, M. Flexural fatigue behaviour of recycled tyre polymer fibre reinforced concrete. *Cem. Concr. Compos.* **2020**, *105*, 103441. [CrossRef]
37. Abbaspour, M.; Narani, S.S.; Aflaki, E.; Moghadas Nejad, F.; Mir Mohammad Hosseini, S.M. Strength and swelling properties of a waste tire textile fiber-reinforced expansive soil. *Geosynth. Int.* **2020**, *27*, 476–489. [CrossRef]
38. Abbaspour, M.; Aflaki, E.; Moghadas Nejad, F. Reuse of waste tire textile fibers as soil reinforcement. *J. Clean. Prod.* **2019**, *207*, 1059–1071. [CrossRef]
39. *ASTM C150/C150M-22*; Standard Specification for Portland Cement. ASTM: West Conshohocken, PA, USA, 2022. [CrossRef]
40. *ASTM C192/C192M*; Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory. ASTM: West Conshohocken, PA, USA, 2025. [CrossRef]
41. *ASTM C143/C143M*; Standard Test Method for Slump of Hydraulic-Cement Concrete. ASTM: West Conshohocken, PA, USA, 2020. [CrossRef]
42. *ASTM C138/C138M*; Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete. ASTM: West Conshohocken, PA, USA, 2024. [CrossRef]
43. *BS EN 12390-3:2019*; Testing Hardened Concrete. British Standards Institution: London, UK, 2019.
44. *ASTM C496/C496M*; Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens. ASTM: West Conshohocken, PA, USA, 2017. [CrossRef]
45. *ASTM C78/C78M*; Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading). ASTM: West Conshohocken, PA, USA, 2022. [CrossRef]
46. Rabie, M.; Bahadori-Jahromi, A.; Shaaban, I.G. Optimisation of Glass and Carbon Fibre-Reinforced Concrete with External Enzymatic Self-Healing: An Experimental and Environmental Impact Study. *Buildings* **2025**, *15*, 3455. [CrossRef]
47. Ben-Alon, L.; Loftness, V.; Harries, K.A.; DiPietro, G.; Hameen, E.C. Cradle to site Life Cycle Assessment (LCA) of natural vs conventional building materials: A case study on cob earthen material. *Build. Environ.* **2019**, *160*, 106150. [CrossRef]
48. Jiménez, C.; Barra, M.; Josa, A.; Valls, S. LCA of recycled and conventional concretes designed using the Equivalent Mortar Volume and classic methods. *Constr. Build. Mater.* **2015**, *84*, 245–252. [CrossRef]
49. *ISO 14044:2006/Amd 2:2020*; Environmental Management—Life Cycle Assessment—Requirements and Guidelines. ISO International Organization for Standardization: Geneva, Switzerland, 2020.
50. Koffler, C.; Amor, B.; Carbajales-Dale, M.; Cascio, J.; Conroy, A.; Fava, J.A.; Gaudreault, C.; Gloria, T.; Hensler, C.; Horvath, A.; et al. On the reporting and review requirements of ISO 14044. *Int. J. Life Cycle Assess.* **2020**, *25*, 478–482. [CrossRef]
51. Mohebbi, G.; Bahadori-Jahromi, A.; Ferri, M.; Mylona, A. The Role of Embodied Carbon Databases in the Accuracy of Life Cycle Assessment (LCA) Calculations for the Embodied Carbon of Buildings. *Sustainability* **2021**, *13*, 7988. [CrossRef]
52. Blay-Armah, A.; Mohebbi, G.; Bahadori-Jahromi, A.; Fu, C.; Amoako-Attah, J.; Barthorpe, M. Evaluation of Embodied Carbon Emissions in UK Supermarket Constructions: A Study on Steel, Brick, and Timber Frameworks with Consideration of End-of-Life Processes. *Sustainability* **2023**, *15*, 14978. [CrossRef]
53. Jones, C.; Hammond, G. *Embodied Carbon—The ICE Database*; Circular Ecology: Worcester, UK; University of Bath: Bath, UK, 2019.
54. Dsilva, J.; Zarmukhambetova, S.; Locke, J. Assessment of building materials in the construction sector: A case study using life cycle assessment approach to achieve the circular economy. *Heliyon* **2023**, *9*, e20404. [CrossRef] [PubMed]
55. Neocleous, K.; Angelakopoulos, H.; Pilakoutas, K.; Guadagnini, M. Fibre-reinforced roller-compacted concrete transport pavements. *Proc. Inst. Civ. Engineers. Transp.* **2011**, *164*, 97–109. [CrossRef]
56. Liew, K.M.; Akbar, A. The recent progress of recycled steel fiber reinforced concrete. *Constr. Build. Mater.* **2020**, *232*, 117232. [CrossRef]

57. Samarakoon, S.M.S.M.K.; Ruben, P.; Wie Pedersen, J.; Evangelista, L. Mechanical performance of concrete made of steel fibers from tire waste. *Case Stud. Constr. Mater.* **2019**, *11*, e00259. [CrossRef]
58. Baričević, A.; Jelčić Rukavina, M.; Pezer, M.; Štirmer, N. Influence of recycled tire polymer fibers on concrete properties. *Cem. Concr. Compos.* **2018**, *91*, 29–41. [CrossRef]
59. Chen, M.; Chen, W.; Zhong, H.; Chi, D.; Wang, Y.; Zhang, M. Experimental study on dynamic compressive behaviour of recycled tyre polymer fibre reinforced concrete. *Cem. Concr. Compos.* **2019**, *98*, 95–112. [CrossRef]
60. Ouda, A.S. Development of high-performance heavy density concrete using different aggregates for gamma-ray shielding. *Prog. Nucl. Energy* **2015**, *79*, 48–55. [CrossRef]
61. Iqbal, S.; Ali, I.; Room, S.; Khan, S.A.; Ali, A. Enhanced mechanical properties of fiber reinforced concrete using closed steel fibers. *Mater. Struct.* **2019**, *52*, 56. [CrossRef]
62. Leone, M.; Centonze, G.; Colonna, D.; Micelli, F.; Aiello, M.A. Fiber-reinforced concrete with low content of recycled steel fiber: Shear behaviour. *Constr. Build. Mater.* **2018**, *161*, 141–155. [CrossRef]
63. Huang, Y.; Kong, D.; Li, Y.; Zhou, S.; Shu, J.; Wu, B. Effect of different shapes of steel fibers and palygorskite-nanofibers on performance of ultra-high-performance concrete. *Sci. Rep.* **2024**, *14*, 8224. [CrossRef]
64. Shah, S.H.A.; Ali, B.; Ahmed, G.H.; Tirmazi, S.M.T.; El Ouni, M.H.; Hussain, I. Effect of recycled steel fibers on the mechanical strength and impact toughness of precast paving blocks. *Case Stud. Constr. Mater.* **2022**, *16*, e01025. [CrossRef]
65. Leone, M.; Centonze, G.; Colonna, D.; Micelli, F.; Aiello, M.A. Experimental Study on Bond Behavior in Fiber-Reinforced Concrete with Low Content of Recycled Steel Fiber. *J. Mater. Civ. Eng.* **2016**, *28*, 4016068. [CrossRef]
66. Martinelli, E.; Caggiano, A.; Xargay, H. An experimental study on the post-cracking behaviour of Hybrid Industrial/Recycled Steel Fibre-Reinforced Concrete. *Constr. Build. Mater.* **2015**, *94*, 290–298. [CrossRef]
67. Centonze, G.; Leone, M.; Aiello, M.A. Steel fibers from waste tires as reinforcement in concrete: A mechanical characterization. *Constr. Build. Mater.* **2012**, *36*, 46–57. [CrossRef]
68. Han, J.; Zhao, M.; Chen, J.; Lan, X. Effects of steel fiber length and coarse aggregate maximum size on mechanical properties of steel fiber reinforced concrete. *Constr. Build. Mater.* **2019**, *209*, 577–591. [CrossRef]
69. Michalik, A.; Chyliński, F.; Bobrowicz, J.; Pichór, W. Effectiveness of Concrete Reinforcement with Recycled Tyre Steel Fibres. *Materials* **2022**, *15*, 2444. [CrossRef]

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