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Sustainable design and carbon-credited application framework of recycled steel fibre reinforced concrete

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ABSTRACT

Waste tires pose significant environmental, health, and fire risks. Creative waste management solutions, including reuse, recycle and repurpose, are necessary to mitigate those impacts while enriching their valorisation. An innovative solution is the upcycling of recycled steel fibre (RSF) from waste tires to enhance strength and durability of concrete. This study thus experimentally examines dynamic and mechanical behaviours of high-strength concrete with varying proportions of RSF, from 0% to 1.2% by volume. The results reveal that high-strength concrete with 1.2% RSF exhibits the best improvement in strengths. In addition, the damping ratio, dynamic modulus of RSF concrete and SEM images confirm valorisation potentials of waste fibres. Via a robust critical lifecycle analysis, the new insights form a new sustainable design and carbon credited application framework for RSF. Our results portray that innovative recycling practices for end-of-life tires yield substantial environmental benefits, including a significant carbon emission reduction.

1. Introduction

The World Business Council for Sustainable Development reports an annual increase of over 25,676 kilotons of end-of-life tires (ELT) (Asia, 2018), which poses significant environmental and health risks caused by the air pollution of toxic chemicals like sulfur dioxide and nitrogen oxides from traditional disposal methods, such as burning, burying (Formela, 2021). Since these pollutants are known to cause respiratory problems, skin irritation, and even cancer, there have been proposals for various tire disposal and recycling methods, including using old tires as fuel and converting tire wastes into construction materials such as rubberised asphalt or crumb rubber (Wang et al., 2020). Due to the urgent need for sustainable construction materials, recycled steel fibre (RSF) has emerged as a popular choice due to its cost-effectiveness and structural reinforcement performance in concrete (Qin and Kaewunruen, 2022).

High-strength concrete (HSC) has become increasingly popular due to high comprehensive performance, and its enhanced durability and load-bearing capacity for concrete structures (Shah and Ribakov, 2011). However, since the ductility decreases with increasing strength, one solution to tackle the defect is incorporating fibres into concrete to provide structural reinforcement (Kang et al., 2011). In particular, industrial steel fibre (ISF) is known to be effective in HSC for increasing significant post-cracking ductility and making the brittle material ductile, which is vital in high-strength concrete applications (Bahmani and Mostofinejad, 2023).

According to Shaikh et al. (2020), incorporating fibres into concrete can enhance concrete's mechanical properties and durability. Fibres can be made of various materials, such as steel, synthetic polymers, and natural fibres. Among them, steel fibres have been extensively studied due to their widespread application (Balendran et al., 2002). As proven by Wang et al. (2021), adding ISF in concrete considerably increases the strength, ductility, and toughness due to the resistant effect to cracking and damage. Furthermore, it is also worth mentioning that fibres contribute to improving concrete's lifespan and reducing its maintenance need. Similar to the industrially manufactured ISF, RSF from waste tires is proven to be a possible substitute for ISF. Althoey et al. (2023) conclude that RSF can significantly improve tensile strength, which coincides with Ali et al. (2022) finding that RSF with the same fibre volume is 61%–77% as effective as industrially produced steel fibre in enhancing flexural-tensile properties. A brief review shows that the effectiveness of ISF in concrete depends on several factors, including fibre types and quantity, concrete mix design, and construction techniques. Meanwhile, appropriate fibre dosage and distribution are crucial because neither excessive nor insufficient fibre contributes to any positive concrete property (Al-Rousan et al., 2023). Additionally, fibres can

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affect concrete workability and finishing. For example, the balling effect of fibres can increase the concrete slump, which leads to a non-uniform distribution of fibres, ultimately making the mechanical property improvement less effective.

As mentioned above, the inherent uncertainty of fibre reinforced concrete makes it challenging to conduct systematic performance evaluation without destructive experiments. Therefore, non-destructive testing has been in the academic spotlight, with structural health monitoring (SHM) through continuous vibration measurements emerging as a major solution (Kot et al., 2021). Radiation and electromagnetic methods are two primary non-destructive techniques used in SHM for concrete with magnetic additive fibres (Eva et al., 2020). The principal function of these methods is to analyse the physical properties of steel fibres to predict the mechanical properties of the concrete. However, both methods are time-consuming and labour-intensive. Additionally, the results are used to overlooks the interaction between the concrete and steel fibres. Furthermore, these methods employ radiation techniques for structural evaluation. The necessary radiation source configuration in the components can pose potential harm to users, leading to debates regarding their applicability (Kobaka et al., 2019). Besides these, the X-ray computed tomography radiation(X-ray) method also focuses on identify the physical properties of steel fibres. However, it aims to understand the random distribution model of steel fibres, utilising this model for finite element modelling to provided theory foundation for predicting the performance of concrete in the future. According to the experiments results from Kruschwitz et al. (2022) which use both spectral induced polarization (SIP) and X-ray methods has found that in SIP, the primary orientation of steel fibres aligns with the direction of lowest resistivity. X-ray scans have revealed a statistically significant mathematical relationship between the distribution of fibres and SIP results. In addition to these methods, infrared thermography (Zhong and Nsengiyumva, 2022) and ground penetrating radar (Manhães et al., 2022) are also popular non-destructive testing for test steel fibre reinforced concrete structures. However, this paper proposes an alternative, economically viable, safe, and potentially applicable non-destructive testing method that has not yet been extensively studied: vibration-based modal test.

Recent continuous vibration-based monitoring have been employed in various structures, including long-span bridges, footbridges, and historic structures. In these structures, concrete material systems have three main interrelated dynamic properties, such as dynamic elasticity modulus, natural frequency, and vibration damping (Razak and Choi, 2001). Each of the properties serves a specific function. Initially, dynamic modulus characterises the material's dynamic response. Meanwhile, natural frequency relates to both the material and structural system, which show high-sensitivity to the crack the void hole inside the concrete or structure. Besides, damping represents the material's energy dissipation. Since its manifests to be the decay of free vibrations, damping is valuable for structures due to its ability to mitigate hazards, such as accidental loading, wind, ocean waves, and earthquakes (Zheng et al., 2008). Therefore, vibration damping also increases individual comfort for utilising the structures while enhancing overall reliability.

Although there has been an increasing number of studies on the performance of concrete mixed with RSF, the concluded findings are rather varied. As RSF is produced by processing collected scrap containing steel, such as used tires it offers a sustainable waste disposal solution while reinforcing concrete structures (Surehali et al., 2023). However, RSF quality can vary according to the source and processing techniques, which may lead to inconsistencies. In contrast, made from high-quality steel wire, ISF are specifically designed for concrete reinforcement, making it easy for them to come in various shapes, sizes, and configurations for specific needs. Meanwhile, thanks to the established standards including ASTM A820, ISF undergoes rigorous quality control processes, ensuring consistent performance. This paper aims to address the substantial differences between RSF and ISF by studying a more stable type of RSF. In the production projects, fibres harvested from steel beads in waste tires are cut before producing recycled hooked-end steel fibres, ensuring more consistent material properties across the applications.

Despite the abundance of research on RSF concrete, most studies primarily focus on the material's mechanical strength, but leave its dynamic properties underexplored. Additionally, the environmental impact of RSF and a tire's life cycle have been largely overlooked in existing evaluation methods. In today's architectural design concepts, besides the fundamental aspect of safety, maximizing economic and environmental benefits is equally crucial. Therefore, this study seeks to fill these gaps by developing ISF and RSF concrete with varying mechanical and dynamic properties to offer a more comprehensive understanding of RSF's role in enhancing concrete performance and ensuring sustainable development. In this way, a life cycle analysis of RSF is conducted to further highlight the recycled fibres' contribution to sustainability and circle economy.

2. Research significance

In practice, ISF are highly regarded for their crack control capabilities, as they can transmit tensile stresses across crack surfaces when micro-cracks occur. This exceptional bridging ability provides significant resistance to the shear forces acting on forming cracks. Due to their excellent shear resistance, many structures, such as large-span bridges and high-rise buildings, use ISF reinforced concrete beams or columns. This reinforcement not only enhances the shear capacity of these structures but can also replace some stirrups, leading to cost savings and environmental-friendly. In the realm of concrete structural with ISF design, the mainstream guideline TR63 has been found to base its shear assessment of steel fibre reinforced concrete beams on the CMOD tests. Past experiments indicate that RSF concrete may exhibit CMOD curves similar to those of ISF concrete. Consequently, RSF could be a promising unconventional reinforcement in concrete components under shear stress, potentially replacing ISF. This substitution would not only contribute to environmental protection but also reduce costs, demonstrating RSF's potential in modern structural engineering.

As a kind of an emerging material, RSF has been primarily studied for its mechanical properties. However, little to no focus has been on its dynamic properties because of, the possibly unpredictable performance of RSF due to the various raw materials used in its production. To address these challenges, this study proposes a novel type of RSF processed from steel beads in waste tires. After identifying the gaps in existing research, this study aims to focus on the following aspects. Initially, the experiments are dedicated to exploring the enhanced material properties. Indeed, incorporating different steel fibres into concrete can significantly improve its mechanical properties, including toughness, splitting strength and flexural strength. This research will compare the efficacy of RSF to ISF regarding their performance in enhancing concrete. Moreover, this study examines the dynamic properties of concrete reinforced with ISF and RSF because understanding the influence of these fibres on the natural frequency, damping ratio, and dynamic modulus can provide valuable insights, which helps make informed decisions in material selection for specific applications. Moreover, related experiments hope to find the potential relationship between the natural frequency and mechanical properties of ISF and RSF reinforced concrete, which can lead to the non-detective application in real construction activity. Besides, this study also looks into the sustainability and resource management. As sustainability becomes increasingly critical across all sectors, using recycled materials in construction is of paramount importance. Therefore, by providing pivotal data on the effective utilisation of waste tires oriented RSF in concrete, this study offers a comprehensive life cycle analysis of waste tire recycling regarding RSF production, which contribute to support the strategy of circle economy.

Therefore, the primary objective of this study is a thorough performance analysis of the new RSF, which hopes to provide fresh insights into its impact on the mechanical and dynamic properties of concrete. Then, this paper moves on to review and summarise the recycling process of waste tires comprehensively analyse a tire's life cycle and its contribution to circular economy. Ultimately, the findings hope to offer valuable contributions to the construction industry, enhancing material performance, promoting sustainability, and potentially reducing costs. After clarifying the research purposes and objectives Fig. 1 is constructed to understand the research significance of this study better.

3. Experimental setup

3.1. Materials

This experiment has adopted Rugby High Strength Cement CEM/I, which adheres to the British Standard (BS EN 197–1) in terms of physical and mechanical properties. Initially, the coarse and fine aggregate materials have been sourced from a reputable supplier known as Tarmac Trupak of Plumtree Farm Industrial Estate in Birmingham, UK, which possesses a specific gravity of 2.5 and a bulk density of 1700 kg/m^3. Then, the coarse aggregate has been crushed to granite with a nominal size of 10 mm, exhibiting a specific gravity of 2.5 and a bulk density of 1650 kg/m^3.

In order to conduct the comparison, Novocon® HE-1050 from the SIKA company has been adopted as ISF to compare the performance to that of RSF. As shown in Table 1, The ISF have an average diameter of 1 mm and a length of 50 mm. The tensile strength of ISF is average of 1150 MPa. On the other hand, the RSF has been obtained from bead wires in tires, collected from Xiang He tire recycling company. Besides, to enhance the performance of the RSF during the bead wire shredding process, the RSF has been with the hook end, which is a rather new technique.

Lastly, to evaluate the RSF properties, 50 fibres are randomly selected. After measuring their dimensions, the fibres have an average diameter of 1.62 mm and a length of 50.1 mm. Furthermore, five RSF have been randomly selected for the fibre tensile strength test, as shown in Fig. 2. The average RSF tensile strength is determined to be 2072.94 MPa with coefficient of variation is 6.47%. According to the comparison between the appearance of RSF and ISF in Fig. 3, the surface of RSF is covered by black rubber powder produced when the tyre rotates at high speed in the steel wires recovery process.

3.2. Mix proportions

The M0 group serves as a reference for various fibre replacement ratios, including 0% for reference, 0.4%, 0.8%, and 1.2%. The mass ratio of cement, water, sand, and stone in the concrete mix is 1:0.54:1.7:2.3. The water/cement ratio of all mixtures is 0.54, and the cement dosage is 317.3 kg/m^3, Table 2 presents the design of combination schemes featuring four different content levels. 、

In the conducted experiment, the optimal fibre content was determined to be 1.2%. This selection was influenced by a combination of recommendations from the ISF manufacturer (SIKA company) and findings from existing literature about RSF (Qin and Kaewunruen, 2022). Research indicates that while an increase in RSF content above 1% does contribute to enhanced flexural strength, the efficiency of this improvement markedly decreases compared to the range of 0.5%–1% (Qin and Kaewunruen, 2022). Furthermore, according to the recommendation guidelines of SIKA company, it is suggested the ISF content below 60 kg, which corresponds to approximately 0.8%. Moreover, the potential risk of balling effect will be increased with the increasing fibre content which have negatively impact the homogeneity and overall performance of the concrete. Therefore, after a thorough evaluation of both ISF and RSF properties, a fibre content of 1.2% was adopted for the experiment. This percentage was chosen to optimize the balance between structural enhancement and the avoidance of issues commonly associated with higher fibre contents, such as reduced workability and potential for non-uniform distribution within the concrete.

Fibre reinforced concrete presents unique challenges compared to traditional reinforced concrete, particularly concerning the 'balling effect.' This issue arises when fibres within the concrete matrix tend to clump together, forming clusters (Zakaria et al., 2017). Such clumping disrupts the uniformity of the concrete and compromises its structural integrity. To mitigate the risk of the balling effect, compliance with the BS EN 12350-1 and 12350-2 standards is critical. These standards provide guidelines for ensuring the homogeneous mixing of concrete. The key strategies employed are as follows.

- Gradual incorporation of fibre: fibres are added in a phased manner, especially at higher concentrations (0.4%, 0.8%, and 1.2%). This staggered approach ensures a more even distribution of fibres throughout the concrete, preventing clumping.
- Extended mixing duration: based on the BS EN 12350-1 standards, the duration of the mixing process is increased slightly. This extended mixing helps achieve a more consistent and uniform concrete mixture.
- Conducting slump tests: Slump tests are routinely performed to monitor the consistency of the concrete mix. These tests are crucial in detecting any irregularities or deviations in the mix's uniformity.

3.3. Experiment and test methods

This study examining the mechanical and dynamic properties of RSF and ISF reinforced concrete. In this context, cylindrical specimens are 100 mm in diameter and 200 mm in height fabricated for splitting tests, and made into 100 mm cubes for compressive strength tests. Besides, notched beams with a dimension of 150 mm × 150 mm in cross-section and 600 mm in length are cast for the residual flexural strength tests and modal tests. In the scope of this study, for each experimental procedure, with the exception of the CMOD test, a set of three samples will be systematically tested to ensure replicability and reliability of results. The ensuing sections will provide a comprehensive analysis, presenting the averaged results of these tests. To enhance comprehension of the various test setups, Fig. 4 illustrates each configuration in detail. The subsequent sections will delve into the specifics of the experimental setup for each test, providing an in-depth understanding of the methodologies employed.

3.3.1. Compressive strength

As can been seen in **Figurer 4(a)**, following the guidelines of BS EN 12390–3:2009, the compressive strength tests in this study apply the concrete cubes with a dimension of 100 mm × 100 mm × 100 mm, which has been cured at a water tank for 28 days. The cubes are then tested at a loading rate of 0.6 MPa/s, with the mix proportions for the concrete specimens as described in section 3.2. Before the test, the specimens are cured in an airtight moist container stored at 20 °C in a laboratory environment. The compressive strength values reported in this study is the average value of three tested concrete specimens.

3.3.2. Split tensile strength test

Three cylindrical samples with a diameter of 100 mm and a height of 200 mm are cast for each mix type, with the split tensile strength determined as per strength at the curing age of 28 days which shown in Fig. 4(b). In this way **Equation (1)** has been used to calculate the split tensile strength of the cylinder:

$$f_{sp} = \frac{2P}{\pi DL} \tag{1}$$

where f_{sp} is the split tensile strength; P represents the maximum applied splitting load; L stands for the length of specimen, and D represents the diameter of the samples.

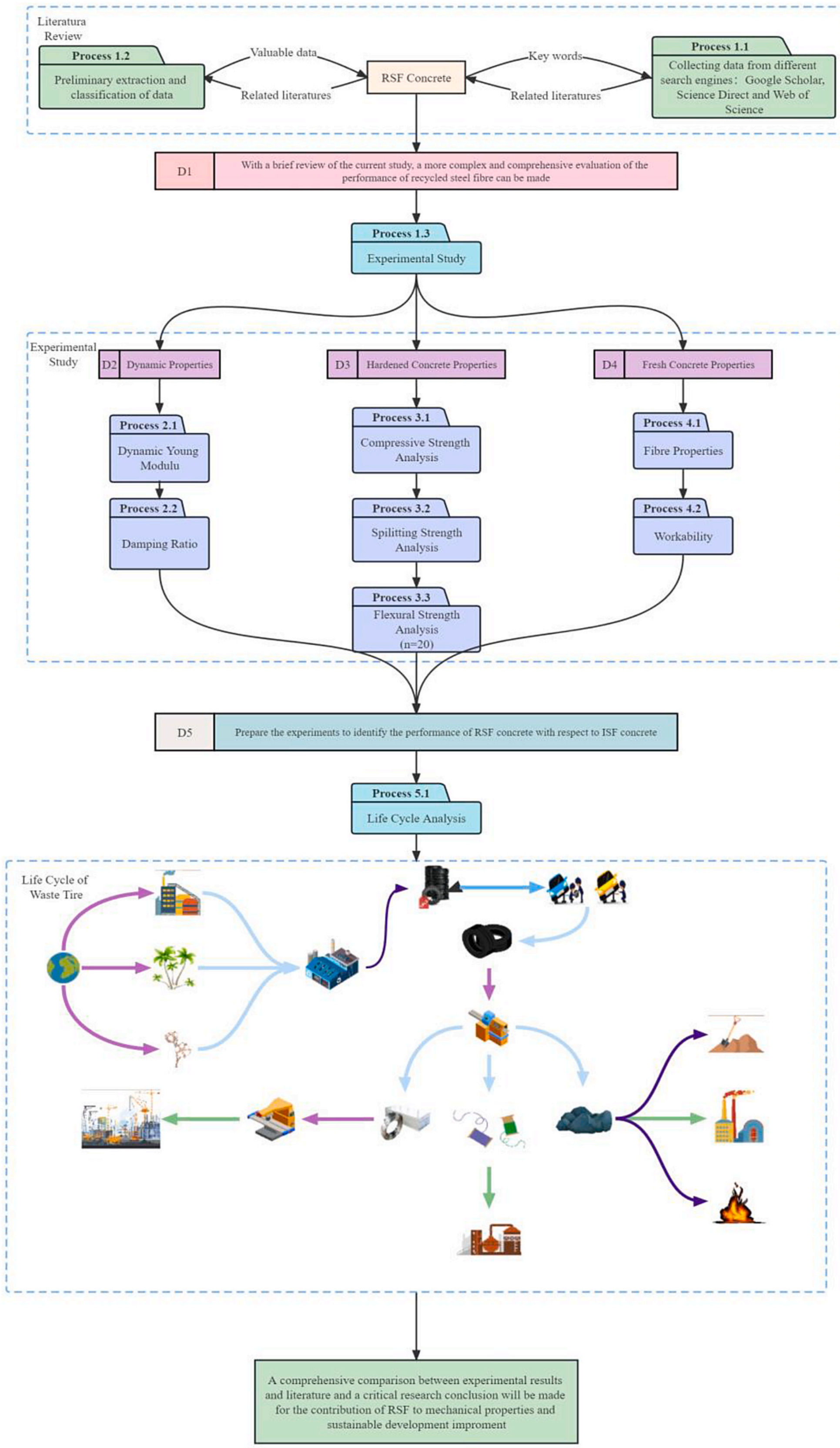


Fig. 1. Research Route about Experimental and Sustainable Evaluation of RSF concrete (Fiksel et al., 2011; Formela, 2021; Qin and Kaewunruen, 2022).

Table 1
Comparison between the RSF and ISF.

RSF		ISF	
Tensile Strength	2072.94 MPa	Tensile Strength	1150 MPa
Raw Material	Scarp bead wire	Raw Material	Steel plate
Diameter	1.62 mm	Diameter	1 mm
Length	50.1	Length	50 mm
Aspect Ratio	30.92	Aspect Ratio	50
Surface	Covered by Rubber Dust	Surface	Clean

Fig. 2. Test setup for tensile strength test of RSF.

3.3.3. *Flexural strength test*

The Crack Mouth Opening Displacement (CMOD) test is widely recognised as a method to characterise the fracture behaviour of materials, including those exhibiting ductile behaviours in particular. By measuring the displacement at a specimen's crack tip of as the applied load, the CMOD test can calculate the fracture toughness of a material. In this way, this method is particularly beneficial to materials with nonlinear behaviours, such as metals and polymers, which are frequently employed in the aerospace, automotive, and civil engineering industries. Therefore, this concrete beams 150 mm × 150 mm × 600 mm in dimension has a notch 25 mm in depth and 5 mm in width cut at the mid-span of each beam. Then, after the notched beams are placed in a 500 kN hydraulic testing machine in a three-point loading setup, the CMOD measurements can be obtained by installing one of the CMOD gauges at the notch, with all tests displacement-controlled according to BS EN 14651 standard. The loading rate was based on the suggestions in BS EN 14651, which maintain the initial loading rate at 0.05 mm/min, and increased to 0.2 mm/min once the CMOD reaches 0.1 mm. The test setup is described in Fig. 4(c). To calculate the limit of proportionality, Equation (2) is applied:

$$\sigma = \frac{3PL}{2bh_{sp}^2} \tag{2}$$

where P is the ultimate point load; L represents the effective span of the specimen; b refers to the width of the sample, and h_{sp}^2 stands for the distance between the tip of the notch and the top of the specimen. Therefore, incorporating fibres in the concrete beam transforms the materials from brittle to elastoplastic. After reaching the maximum flexural strength, the fibre-reinforced concrete beam can avoid a sudden damage like plain concrete. However, due to the bridging effect of fibres, the specimens have a certain residual strength. In this way, **Equation (3)** has been proposed to define this flexural residual strength ($f_{R,j}$).

$$f_{R,j} = \frac{3F_jL}{2bh_{sp}^2} \tag{3}$$

3.3.4. *Modal test*

As a non-destructive testing method to evaluate the dynamic characteristics of structures and materials modal testing involves the subject of a structure to a known force or vibration, subsequently measuring its

Table 2
Concrete mix.

Group	Cement (kg/m^3)	Water (kg/m^3)	Sand (kg/m^3)	Gravel (kg/m^3)	Fibre (kg/m^3)
M0	317.3	171.34	983.63	713.925	0
M1-ISF	317.3	171.34	983.63	713.925	24(0.4%)
M2-ISF	317.3	171.34	983.63	713.925	48(0.8%)
M3_ISF	317.3	171.34	983.63	713.925	24(0.4%)
M1-RSF	317.3	171.34	983.63	713.925	48(0.8%)

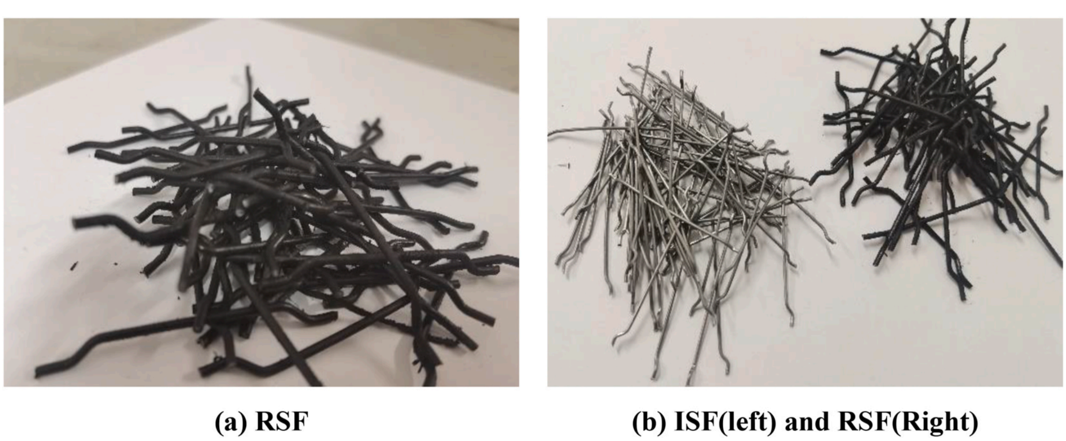


Fig. 3. Comparison between the RSF and ISF.

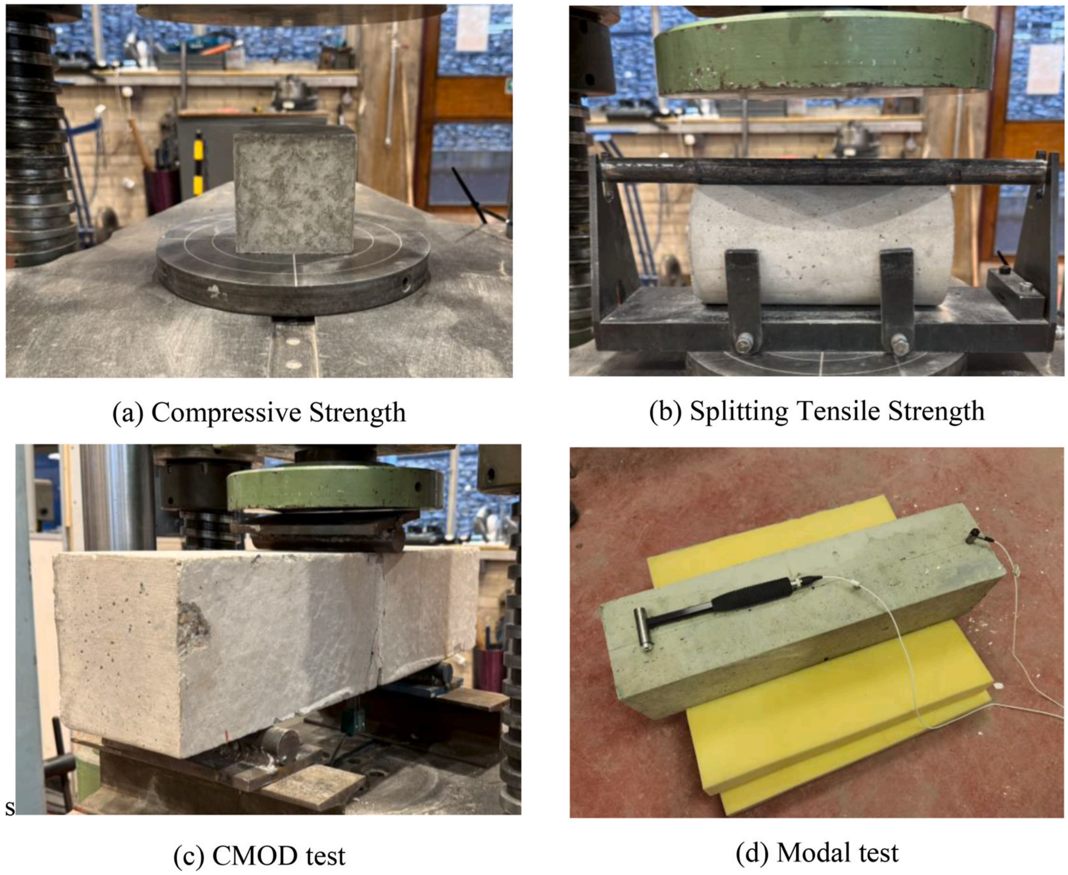


Fig. 4. Test setup.

response to ascertain its natural frequencies and damping ratios (Ospitia et al., 2022). In addition to being invaluable to assess the structural integrity and performance of the fibre reinforced concrete without damaging the specimens, such information can also help monitor the quality of fibre reinforced concrete applications.

There are three major results from the modal test: natural frequency, damping ratio, and dynamic young's modulus. Among them, dynamic young's modulus aims to describe the material's ability to resist deformation when subjected to dynamic stress, such as the oscillatory and cyclic loading, which contribute to the structure designs subjected to vibrations, impacts, and seismic activities. Therefore, the modal test setup in this study has been prepared as illustrated in ASTM C215, with **Equation (4)** used to calculate the dynamic young's modulus (E) according to ASTM C215:

$$E = CMn^2 \tag{4}$$

where M refers to the mass of specimen; n stands for the fundamental transverse frequency, and C is 0.9464(L^3T/bt^3) for prism. Similar to other modal test examples in the literature, two sponge mats with a thickness of 500 mm have been placed above all test to provide a free-free condition in this study which shown as Fig. 4(d).

3.3.5. Scanning electron microscopy

To evaluate the micro-structure of fibre reinforced concrete, scanning electron microscopy (SEM) employ in this study, whose procedure is conducted according to the ASTM C1723-2010 standard (Belli et al., 2020). Initially, the small broken samples prepared are dried at 40 °C in oven. Then, the samples are sprayed with gold. Following the preparation, SEM is employed to obtain the electron-backscattered images, which are magnified 1000 times from the original size. The SEM image resolution of the concrete samples in this study is between 200 and 500 μm, with a image size of 1280 x 1040 pixel.

4. Experimental results and discussion

This chapter aims to provide a comprehensive analysis on the performance of RSF and ISF concrete. By comparing the RSF and ISF concrete, RFS's contribution to concrete performance improvement can be evaluated significantly, with the fresh and mechanical properties of RSF and ISF concrete listed in Table 3.

4.1. Slump test

Table 3 illustrates the slump test results with various fibre contents. As anticipated, adding fibres can significantly decrease the slump value. According to Faris et al. (2021), the steel fibres reduce the workability of geopolymer concrete, while the hooked-end fibres create a higher flow resistance in fresh geopolymer concrete. Moreover, the slump of ISF concrete appears to be lower than that of RSF concrete when the fibre content is kept constant, which is attributed to the rubber dust surrounding the RSF surface, preventing the fibres from absorbing a certain amount of water during hydration(Roychand et al., 2020). Due to the hydrophobic nature of rubber, the rubber coating on RSF reduces its water absorption capacity. This results in a slightly higher slump in RSF concrete compared to ISF concrete, with an increase of 3.7% and 2.1% at fibre contents of 0.4% and 1.2%, respectively. For both ISF and RSF, it can conclude that the addition of fibres in concrete significantly affects its workability. When maintain the fibre content at 1.2%, the slump values for both ISF and RSF concrete exhibit a notable decrease, which is 27.2% and 26.1% reduction in comparison to traditional concrete for ISF and RSF concrete. The experimental results of this study exhibit trend consistent with previous literature (Bjegovic et al., 2014; Leone et al.,

Table 3
Test results of ISF and RSF concrete.

Mechanical Properties Group	Slump (mm)	Compressive Strength (MPa) Avg ± SD	COV	Splitting Strength (MPa) Avg ± SD	COV	Flexural Strength (MPa)
M0	65	58.69 ± 1.15	1.96%	3.35 ± 0.10	2.87%	2.04
M1-ISF	54	64.15 ± 0.39	0.61%	4.25 ± 0.12	2.83%	3.05
M2-ISF	49	66.14 ± 2.01	3.03%	4.35 ± 0.3	6.96%	3.31
M3_ISF	47	66.90 ± 2.29	3.43%	5.20 ± 0.25	4.76%	4.59
M1-RSF	56	62.16 ± 1.25	2.01%	3.85 ± 0.07	1.91%	2.94
M2-RSF	49	64.62 ± 0.74	1.14%	4.24 ± 0.14	3.26%	3.25
M3_RSF	48	65.26 ± 0.39	0.60%	4.44 ± 0.09	1.95%	3.72

*The flexural strength results calculated from the CMOD test. Avg is the average results, SD is the standard deviation, and COV is the coefficient of variation.

2016; Rossli and Ibrahim, 2012; Samarakoon et al., 2019). However, a notable finding is that RSF derived from steel wires demonstrate a reduced tendency to form balls during the concrete mixing process. This observation contrasts with the behavior of RSF recovered from steel belts, which are more prone to balling due to their irregular shapes and propensity to entangle. The difference can be attributed to the distinct recycling technologies used. In our study, the RSF sourced from steel wires maintained a consistent shape, contributing to a more stable performance compared to the more irregular RSF. In addition, the results indicate that the interaction between RSF and cement during mixing is more influential than ISF because the water absorbed by the rubber dust can cover the RSF.

4.2. Compressive strength test

According to Table 3, the addition of fibres increases the compressive strength for both fibre geometries. On the contrary, the compressive strength of the concrete with a fibre content of 1.2 % is similar to specimens with a fibre content of 0.8% because incorporating fibres into the mixtures makes consolidation more challenging, increasing the entrapped air. According to Johnston and Skarendahl (1992), fibres have little intrinsic effect on the compressive strength. However, such an effect is indirect and mainly dependent on whether fibre types and quantities can decrease the consolidation degree in the matrix. The average compressive strength of the RSF concrete in 28 days is 15–20% higher than the plain concrete. Meanwhile, according to the results, adding ISF in concrete exhibits higher compressive strength than RSF concrete, which are 21.10% higher in M1-ISF than M1-RSF, 8.86% higher in M2-ISF than M2-RSF, and 9.14% higher in M3-ISF than M3-RSF. The experimental results indicated that, compared to RSF concrete, ISF concrete exhibits higher compressive strength at equal fibre content. This phenomenon can primarily be attributed to the inferior hydration capacity of RSF concrete (Roychand et al., 2020). The presence of rubber particles on the surface of RSF impedes the hydration reaction, leading to incomplete hydration and, consequently, a reduction in the strength of the concrete matrix.

The compressive strength improvement has caused a poorer performance of RSF concrete because of the poor quality of RSF. Indeed, since RSF is recovered from waste tire, which already suffers from the fatigue and ductility damage, the fibre surface is surrounded by rubber dust, leading to the poor bonding between fibre and cement paste. Meanwhile, the rubber dust gives rise to a weak interfacial transition zone, which may have contributed to the limited strength improvement (Niş et al., 2023). Therefore, adding steel fibre improves the concrete compressive strength, which can be attributed that fibre, particularly steel fibre, can improve the bond between the concrete ingredients while assisting the increase in the bridging effect of the stress concentration and micro or macro cracks. By controlling the fibre content of ISF concrete, it is discernible that an increase from 0.4% to 1.2% results in a marginal alteration in its effective of compressive strength improvement. This trend is paralleled in RSF, which exhibits a comparable low rate of increment. Consequently, there are limited impact of increased fibre content within this range on the compressive strength of these concrete types. While pervious theories posit that adding RSF or ISF to concrete significantly boosts compressive strength through densification of the concrete matrix(Grzymski et al., 2019), this study suggest a different scenario for HSC. In the micro-structure of HSC, which inherently have fewer voids and a more closely knit matrix(Wongpa et al., 2010), the addition of RSF or ISF provides only a marginal increase in strength. This contrasts with the notable improvements observed in normal strength concrete. The already dense composition of HSC, therefore, limits the effectiveness of fibre in further enhancing its compressive strength.

4.3. Splitting strength test

According to the results of 28-day splitting tensile strength for all specimens in Table 3, an increased splitting tensile strength can be observed in ISF concrete from 4.25 MPa to 5.2 MPa, corresponding to the fibre content increased from 0.4% to 1.2%. Similarly, when the RSF dosage is 1.2%, the splitting tensile strength of RSF concrete reaches 4.44 MPa, showing a 32.5% increase compared to plain concrete. Despite the differences, ISF concrete demonstrates a higher tensile strength than RSF concrete, which is a trend diverging from the observed pattern in compressive strength. Regardless of the fibre types, a minimum of 17% strength improvement is noticeable when fibre is added.

Therefore, in light of the compressive strength analysis, the fibre quality appears to influence the improvement efficiency of splitting strength significantly. In particular, the fibre's hook end in the splitting experiment plays a crucial role in enhancing the splitting strength. According to El-Hassan and Elkholy (2021), a robust hook end can resist the formation and progression of minor cracks, thereby bolstering the overall crack resistance of the concrete.

However, it's important to consider that RSF, since RSF is derived from waste tires, it should be considered that one of its raw materials, Bead Wires, may cause sustained fatigue damage, which can significantly diminish the connection force of RSF hook end, thereby reducing RSF's effectiveness in improving the splitting strength (Zhong et al., 2023). In some referenced experiments, RSF were observed to slightly reduce the splitting strength of concrete(Baricevic et al., 2017; Grzymski et al., 2019). This decrease is often linked to the disorganized internal crack development, attributed to the irregularity and inconsistency of fibres, especially those derived from steel belt recycling. Such irregular fibres disrupt the coherence of crack formation, thereby impairing the overall performance of the matrix. However, the experiment in question utilized RSF of uniform shape and produced through a consistent manufacturing process, different from the more chaotic RSF from steel belt recycling. This uniformity in RSF leads to a more homogenous matrix within the concrete, which helps in maintaining the coherence of crack development and enhances the overall stability and performance of the concrete structure.

4.4. CMOD test

4.4.1. CMOD-deflection curve

To study the post-cracking performance of RSF and ISF reinforced concrete beams, the CMOD tests have been conducted according to the BS EN 14651-2005 + A1-2007 standard, with the experimental results summarised in Table 4 and Fig. 5. In these experiments, $f_{R,1}$, $f_{R,2}$, $f_{R,3}$, and $f_{R,4}$ are calculated based on the CMOD curve, representing the residual flexural strength with a CMOD value of 0.5, 1.5, 2.5, and 3.5 mm, respectively.

Table 4 illustrate the significant impact of the volume fractions of ISF and RSF on the mechanical properties of fibre-reinforced concrete. The fibre's bridging effect can prevent the abrupt decline in load-carrying capacity in fibre-reinforced specimens. As the fibre content increases, the flexural strengths of both RSF and ISF concrete show a similar increasing trend as anticipated (Zamanzadeh et al., 2015). However, ISF concrete exhibits a higher residual strength and maximum flexural strength than RSF concrete. According to Table 4, an increase in volume fraction enhances the first-peak strength, peak strength, residual strength, and flexural toughness. In this way, concrete mixtures incorporating ISF exhibit higher toughness and residual strength than those containing RSF.

At a 1.2% fibre volume, the maximum peak load for ISF concrete is approximately 225% higher than that of plain concrete. Similarly, for RSF concrete, the maximum peak load is about 182.3% higher than plain concrete at the same fibre volume. However, unlike the similar improvement of the maximum flexural strength, ISF-reinforced concrete outperforms in improving the post-crack energy and the total energy absorption for bending strength.

When the post-peak load and the subsequent sharp load drop, the load of the ISF concrete with 0.8% fibre content displays a slight increase before plateauing. In contrast, by comparing the concrete beams with 0.4% and 0.8% RSF or ISF content, RSF concrete beams demonstrate a load of proportionality (LOP) comparable to that of ISF concrete because the LOP reflects the flexural tensile strength of uncracked concrete beams, which is primarily dependent on the friction force between the concrete matrix and fibre. Moreover, the hooked end plays a critical role in the crack control after the crack occurs. Once the beams crack, the hooked end sustaining the load contributes to the residual flexural tensile strength (Zia et al., 2023).

Consistent with other experimental studies, our paper also observed that concrete reinforced with RSF struggles to match the flexural performance of concrete reinforced with ISF when both have the same fibre content (Skarżyński and Suchorzewski, 2018; Smrkić et al., 2017; Zamanzadeh et al., 2015). Nevertheless, this study identified a notable exception with RSF obtained from steel wires, as utilized in our research, which exhibited superior performance. Previous studies, like the one by Skarżyński and Suchorzewski 2018, indicated a minimum strength reduction of 3.1% in RSF concrete compared to ISF concrete at a fibre content of 0.25%. In contrast, this study demonstrated a lower LOP for RSF concrete at 0.8% with an only 1.81% strength loss, highlighting the effectiveness of RSF sourced from steel wires.

Table 4
CMOD test results of ISF and RSF concrete.

Result	Residual Flexural Strength (MPa) 28days						
	Plain	ISF			RSF		
	0%	0.40%	0.80%	1.2%	0.40%	0.80%	1.2%
Peak Load	2.04	3.05	3.31	4.59	2.94	3.25	3.72
Fct 0.5	–	2.08	3.50	4.54	1.12	2.90	3.48
Fct 1.5	–	2.01	3.70	4.00	1.21	2.69	3.07
Fct 2.5	–	1.87	3.40	3.60	1.30	2.17	2.72
Fct 3.5	–	1.57	2.84	3.23	1.29	1.90	2.25
	Fracture Energy and Work						
W_f^T(N/m)	–	20.32	38.47	31.32	47.37	55.18	61.91
W_f^{pre}(N/m)	–	0.43	0.52	0.59	1.16	0.55	1.72
W_f^{post}(N/m)	–	19.89	37.94	30.73	46.21	54.63	60.19
G_f^T (J/mm^2)	–	5.42	10.26	8.35	12.63	14.71	16.51
G_f^{pre} (J/mm^2)	–	0.12	0.14	0.16	0.31	0.15	0.46
G_f^{post}(J/mm^2)	–	5.30	10.12	8.20	12.32	14.57	16.05

*W_f^T and G_f^T is the total fracture work and energy, W_f^{pre} and G_f^{pre}.
the fracture work and energy before peak and W_f^{pre}.
and G_f^{post} is the fracture work and energy after peak.

4.4.2. Fracture energy

Fracture energy is defined as a material's capacity to obsorb the post-crack energy, which represents the energy that a structure absorbs during failure. The specific fracture energy G_f (J/mm2) is calculated for the area under the splitting force-displacement curve. According to previous experiments, adding fibres helps improve the resistance of the concrete matrix to cracks. To explain ISF and RSF's ability to improve the fracture energy absorption of the concrete matrix, this study compares the two materials before and after the main crack appears, as shown in Table 4.

The results show that fibres in concrete increases the fracture energy of planar concrete because cracks cannot propagate without stretching and stripping the fibres. Compared to unreinforced concrete specimens, the fracture energy of fibre specimens increases most significantly for M3-ISF specimens, which is up to 16.51 J/mm^2. Therefore, strengthening concrete with RSF can cause a less significant increase in fracture energy than ISF, which are 5.42, 10.26, and 12.63 J/mm^2 respectively when maintaining the fibre content at 0.4%, 0.8% and 1.2%. In this way, although the RSF and ISF's ability to increase the fracture energy is basically similar when the fibre content is kept low, the gap between the two becomes larger as the fibre content gradually increases.

The differential performance in fracture energy improvement between ISF and RSF primarily stems from the varied mechanisms theory for steel fibres enhance the flexural strength of concrete. In the phase leading up to the LOP peak, a key factor is the fibre-matrix interaction. Initially, the fibres bolster flexural strength via frictional forces between their matrix and the concrete base, especially prevalent in the micro-cracking phase(Chen et al., 2021). As the concrete structure progresses towards major crack formation and strength reduction, the role of the fibres evolves. After the LOP peak, when fibres begin to pull out, the hooked ends' anchorage strength becomes crucial(Chen et al., 2021). The CMOD graph's interpretation, where fracture energy is the area under the curve up to the X-axis(Venkateshwaran et al., 2018), highlights this different between ISF and RSF concrete. Initially, both ISF and RSF show similar behaviours up to the LOP point, but significant differences emerge in the residual strength phase which is post-crack development. The underperformance of RSF in the post-crack phase is attributed to the lower strength of their hooked ends. Given that RSF undergoes secondary processing and is often a product of prolonged fatigue, its hooks are inherently weaker. While the difference between RSF and ISF is negligible at low fibre volumes due to limited hook resistance, it becomes pronounced with increased fibre content. ISF, with stronger hooked ends, exhibits a cumulative strength effect not matched by RSF. As a result, the fracture energy gap between RSF and ISF widens, predominantly driven by the compromised integrity of RSF's hooks in the post-cracking phase.

4.5. Failure mode and crack patterns

Table 5 demonstrates crack patterns in various specimens after the flexural tests, in which most specimens exhibit a single crack failure originated from the pre-cut notch. According to the EN 14651 standard, tests with specimens failed outside the notch are invalid. Meanwhile, the majority of specimens does not completely fracture even after 4 mm of deformation, which indicates that fibre maintains a ductile response even with a high damage level. However, as the fibre content increases, the failure mode of the beam changes and becomes more flexible. In particular, although the beam surface appears to fall off when 1.2% of steel fibre is filled under the bridging effect, a certain residual stress is still maintained, which shows that adding steel fibres can obviously improve the structure safety. In addition, after comparing the RSF and ISF performance, both materials have a strong bridging effect. Therefore, when focusing on the failure mode alone, there is little difference between them. However, when combined with the failure mode and load displacement curve, the bridging effect provided by ISF is higher than RSF reinforced concrete with the increasing fibre content,

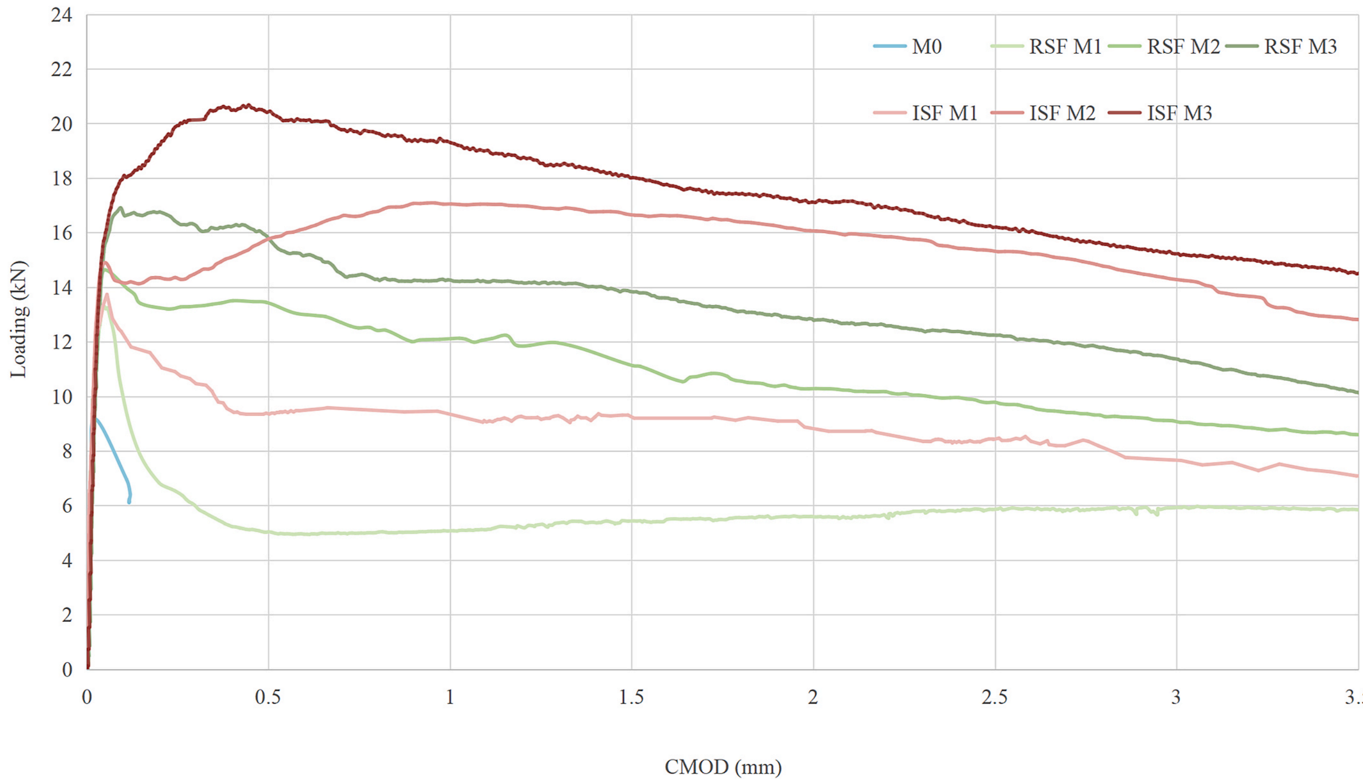


Fig. 5. CMOD-displacement curve.

especially after the crack occurs. Yet, when maintained below 0.8%, this LOP gap is limited with almost no difference between them at 0.4.

Based on Table 5 and the experimental setup, it is observed that the addition of fibres to some extent delays the onset of severe structural failure. With a 1.2% fibre addition, concrete spalling tends to occur before more intense fracturing. The inclusion of fibres enhances the ductility of the structure. Moreover, the failure mode of fibre is also contribution to the increased ductility and the pattern of crack development. In the case of polypropylene fibres, jute fibres, or aluminium fibres, they often exhibit breakage or significant bending at the cross-section after structural failure (Elsayed et al., 2023; Singh et al., 2018; Yin et al., 2016). In this experiment, the primary mode of fibre failure was due to the loss of bonding strength with the concrete or the ineffectiveness of the hooked ends of the fibres in providing pull-out resistance. However, no fibre breakage or significant bending was observed, which is one of the reasons for the slow crack development in this experiment. Moreover, crack development is also related to the concrete's inherent strength, as well as the length and distribution of the fibres. The study from Wang et al. (2019) investigated the effects of fibre length and volume fraction on the mechanical properties and crack resistance of basalt fibre reinforced concrete. It noted that the ability to resist dry shrinkage cracking increases with the increase in the volume fraction of basalt fibres.

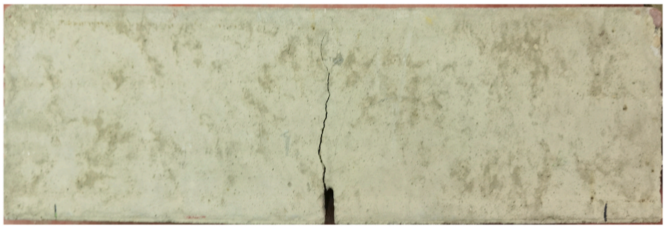
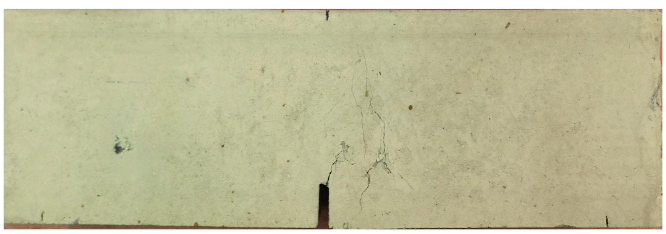
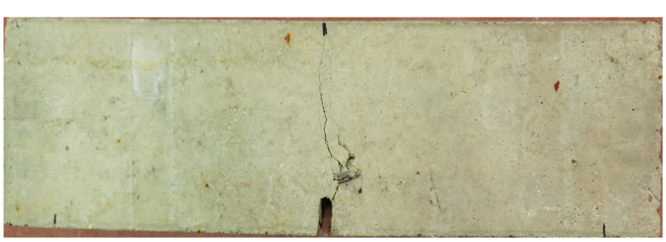
4.6. Dynamic properties

According to Table 6, the dynamic properties for RSF and ISF concrete follows the increase in fracture energy for concrete mixtures with fibre. The natural frequencies of fibre-reinforced concrete with different fibre contents have been studied extensively in recent years. Indeed, adding fibres to concrete can change its dynamic properties that affect the natural frequency and other mechanical properties. Existing studies have shown that increasing fibre content in concrete can increase the natural frequency, making it stiffer and more resistant to dynamic loads. Moreover, increasing the fibre content in ISF and RSF concrete is proved academically to increase the dynamic modulus of elasticity, making it more resistant to dynamic loads. However, the effect of fibre content on dynamic modulus of elasticity is not linear with a limit to the improvement in this property with increasing fibre content. Yet, unlike ISF, RSF concrete is more sensitive to natural frequency. Compared to the M1-RSF, the natural frequency increases to 1385.9 Hz when the fibre content increased to 1.2%. In addition, compared to the natural frequency, adding fibre has little effect on damping ratio. Besides, in terms of trends, RSF demonstrate a higher sensitivity to natural frequency than ISF. With the growing amount of RSF, the growth rate of the natural frequency becomes faster, resulting in a steeper slope.

The effect of fibre addition on the natural frequency and damping ratio of concrete structures fundamentally relates to the structural system's stiffness and internal energy dissipation rate(Kato and Shimada, 1986). The natural frequency of a structure is closely related to its stiffness (Razak and Choi, 2001). It is observed that adding fibres to concrete can enhance the structure's stiffness, thereby impacting its natural frequency. The damping ratio, on the other hand, reflects the internal energy dissipation within the system (Fayyadh and Razak, 2022). In a complete system, most of the energy from external forces is utilized for vibrational motion. In a damaged system, some energy is dissipated through defects, reducing the available vibrational energy. As a result, the damping ratio, which indicates the rate of vibration decay, often increases with the severity of damage or deterioration. In structures that are undamaged or maintain good internal homogeneity, the damping ratio generally remains consistent. This minor influence on the damping ratio is due to its complex relation with internal energy dissipation mechanisms, which are not significantly affected by the addition of fibres, especially in structurally sound systems.

The modal test can provide some basic structure information as a non-destructive testing method. In order to apply non-destructive testing to actual production, combining the experimental results of non-destructive testing to match the mechanical properties of ISF and RSF concrete can improve the understanding and evaluate the structure. According to Fig. 6, illustrating the potential relationship between

Table 5
Failure mode of RSF and ISF concrete.

Specimen	Photograph (Specimen M1-M3 ISF&RSF shown here)	Surface Crack
M1-ISF		As with plain concrete, the main cracks appear at the notch, but with the main cracks bridging of the steel fibres begins
M2-ISF		Compared with the concrete beam with 0.4% fibre content, the main crack appeared significantly delayed.
M3-ISF		Compared with the concrete beam with 0.8% fibre content, a large number of micro-cracks appeared around the main cracks, and with the continuous development of the main cracks, the micro-cracks also appeared around the main cracks. In addition to this, spalling of the concrete surface occurs with the increase of micro-cracks
M1-RSF		Same crack development pattern as 0.4% ISF reinforced concrete beams
M2-RSF		Compared with the concrete beam with 0.4% RSF, the main crack appeared significantly delayed, and there are small cracks around the main cracks which lead to the development of main cracks
M3-RSF		Compared with the concrete beam with 0.8% fibre content, a large number of micro-cracks appeared around the main cracks, which similar with that of ISF with 0.8%.

dynamic and mechanical properties, the relationship between the three mechanical properties and natural frequency is quite evident. Furthermore, the correlation between flexural strength, compressive strength, splitting tensile strength, and natural frequency is high, with all the R-squared values reaching 0.98 or higher.

4.7. Microstructural analysis

The microstructural analysis of the three components in ISF and RSF concrete mixtures, namely cement paste, aggregate, and ISF or RSF fibre, are performed based on Scanning Electron Microscopy. According to Fig. 7(A), comparing the details of ISF and RSF surface, ISF is rougher than RSF, while RSF has a smoother surface than ISF. However, the RSF surface seems to be covered by rubber dust which mainly leads to a

Table 6
Dynamic properties of RSF and ISF concrete.

Properties Group	Natural Frequency (Hz)	Damping Ratio (%)	Dynamic Young Modulus (GPa)	Weight (Kg)
M0	1343	0.97	20.48	32.84
M1-ISF	1357.3	0.92	20.55	32.23
M2-ISF	1363.5	1.1	21.26	32.47
M3_ISF	1378.2	0.97	21.82	33.23
M1-RSF	1358.5	0.83	20.36	31.975
M2-RSF	1376.8	0.82	21.08	32.815
M3_RSF	1385.9	0.99	21.74	33.105

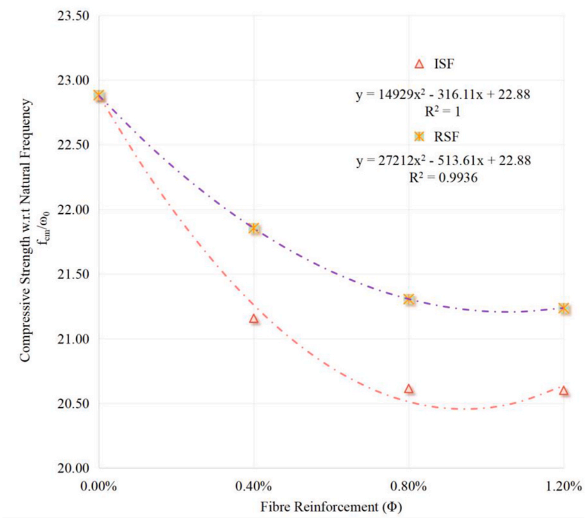
darker RSF surface of RSF rather than a bright metal colour. In addition, Fig. 7(B) and **(C)** describe the inside information of RSF and ISF concrete. According to Fig. 7(B), the surface of ISF wires is uniform after pulled out from the mortar, with the visible regular cracks occurred at the steel wire production stage. Furthermore, a small quantity of slurry cement residue can be seen in the surface pits as tarnish with high calcium content. In this way, the surface of RSF wires is smoother than that of ISF, which can suggest a slightly different production technology or protective coating application.

According to Fig. 7(C), RSF has been partly coated with cement paste despite its smooth surfaces. Even if it is impossible to mention the perfect bonding because of the slippage of ISF from cement paste, the cement paste coated RSF surfaces indicate the bond between cement paste and ISF. The increases in flexural and splitting tensile strengths also demonstrate fibre's contribution on the bond strength. However, the rougher ISF have limited the concrete matrix covered. The main reason of more cement paste coverage of RSF is mainly due to the rubber dust and carbon black on its surface. However, cement encapsulation does not represent the bonding degree between fibres and cement. However, there are also negative effects of carbon black and rubber particles from the side. According to the Zhang et al. (2022), nanoscale particles, such as carbon black and rubber, can absorb a large amount of water while hindering the adequate contact of cement with water. Therefore, the hydration reaction is retarded (Letelier et al., 2023). As it is pointed out by Mohajerani et al. (2020), the bonding with cement does not work well after rubber particles are involved, which results in a significant reduction in the mechanical advantages.

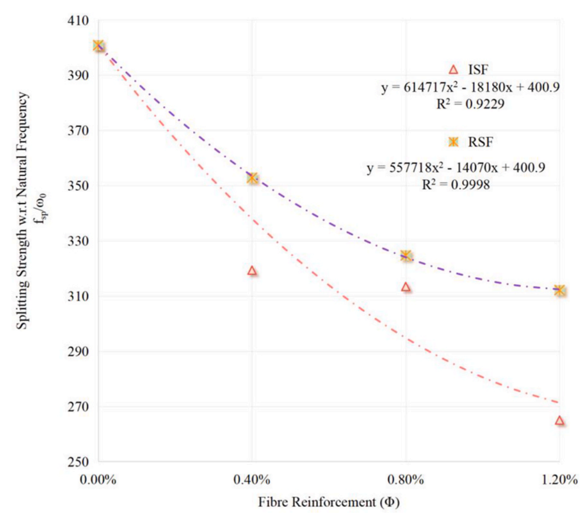
To further comprehend the failure modes between fibre and cements, some pull-out tests were discussed in this study. Aiello et al. (2009) explored the properties of RSF, illustrating that efficiency of bond resistance between RSF and concrete matrix is similar to that of ISF. However, the work principle of the RSF and ISF to concrete matrix are different. The double-sided pull-out tests performed in the study of (Tlemat et al., 2004)revealed that, RSF has a stronger bond compared to ISF during the deployment of micro-cracks. Meanwhile, with the development of crack, the impact of the bonding behaviours gradually diminishes, while the effective mechanical contribution of the hook end steadily increases. The exceptional performance of RSF during the initial phase of crack development can be attributed to the presence of rubber dust and black carbon, which fosters a more effective bond with the cement matrix. On the other hand, ISF has a protective coating that hinders a strong bond with cement surfaces. However, RSF is not without its drawbacks; it has a weaker hooked end, a flaw arising from material fatigue and the bending processes it undergoes. This stands in contrast to ISF, which leverages its robust hooked ends to offer resistance to tension and control cracks efficiently with the development of micro-cracks.

5. Sustainability assessments

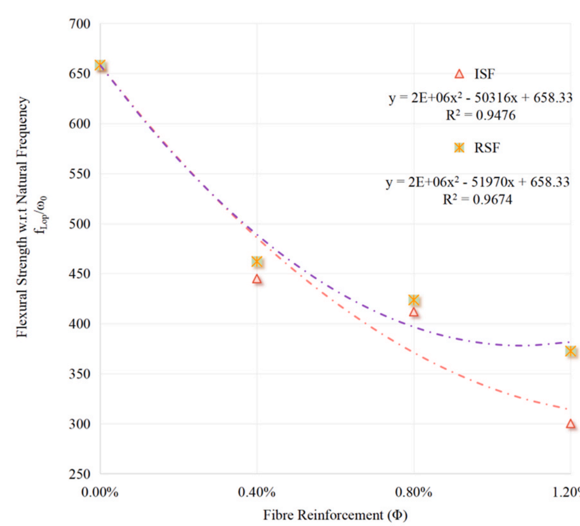
Waste tire management presents a worldwide challenge. Therefore, one comprehensive solution lies in recycling waste tires and converting them into valuable resources (Araujo-Morera et al., 2021). In addition to



(A) Correlation model of f_{cm}/ω_0 with fiber content



(B) Correlation model of f_{sp}/ω_0 with fiber content



(C) Correlation model of f_{lop}/ω_0 with fiber content

Fig. 6. Correlation of dynamic properties and mechanical properties.

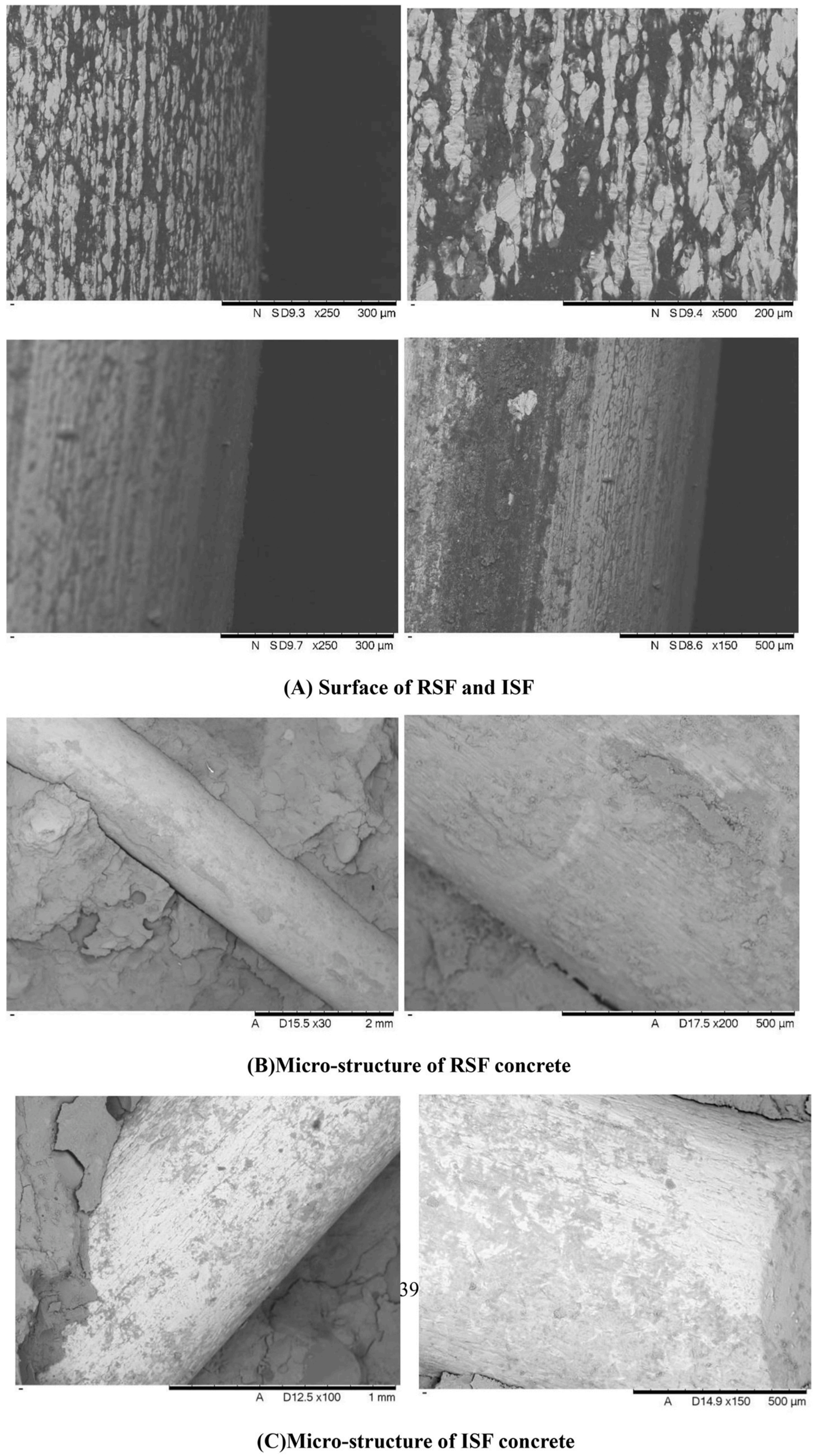


Fig. 7. Microstructure of RSF reinforced concrete.

minimising waste and conserving natural resources, this practice also mitigates environmental pollution. Recycling waste tires may extract potentially valuable materials, such as rubber fillers, steel wires, carbon black, and textiles, which can serve as secondary materials in extensive applications across diverse industries, including construction, renewable fuel production, and tire retrofitting. Furthermore, the beneficial utilisation of these byproducts illustrates the feasibility and potential of recycling initiatives (Hay and Ostertag, 2018).

In the wake of increasing environmental concerns and prevalent extreme weather, the world has seen a surge in promoting the circular economy concept and strategies, which involve shifting from a consumer mindset to an environmental considerations, essentially endorsing practices that protect our surroundings while fuelling the economic growth. However, although waste tires pose an undeniable environmental hazard, their recycling potential remains vastly untapped. Despite the extensive studies into waste tire recycling, there remains a discernible gap in the comprehensive discussions and analyses considering the intertwined economic and environmental implications. Therefore, this study delves into the principles of the circular economy, which hones in on the economic strategies involved in RSF production. This hopes to provide an inclusive examination and analysis of tire recycling and utilisation, foregrounding its critical role in a viable circular economy. Besides, the principle of the circular economy emphasises generating economic benefits while promoting recycling. According to Fig. 1 which has explained the cycle of materials elaborately. To evaluate the contribution of used tire recycling to the realization of the circular economy, this paper focuses on the manufacturing process of RSF and compared the recycling potential with other secondary materials in tires, which conducts a comprehensive review and assessment of waste tire recycling and utilisation.

5.1. Pre-treatment of waste tires

The quest for effective tire recycling and utilisation begins with a thorough understanding of tire composition. Formela (2021) offers an exhaustive analysis of the constituent elements of two predominant types of tires: passenger vehicle and truck tires which shown in Table 7. A comparison of the two kinds makes it possible to better comprehend the specific resources that can be harvested from each tire category. By focusing on the two above-mentioned categories of tires, it becomes evident that although, truck tires are distinct, they contain a higher proportion of natural rubber and a reduced content of carbon black as a reinforcement filler than passenger car tires, which can be attributed to the superior performance characteristics required by passenger car tires, such as low rolling resistance, enhanced skid resistance, and optimal wear (Okoye et al., 2022). From the preliminary analysis, steel, rubber, and textile fibres can be identified as the three most valuable and common components in discarded tires. Therefore, a thorough sustainability evaluation of these three materials hopes to gauge both the commercial potential and sustainable implication of recycling discarded tires. Besides, this dual-pronged assessment enables a comprehensive understanding of the environmental and economic advantages inherent in tire recycling.

Two essential machines are employed to waste tire utilisation in the pre-treatment, which are the Wire Drawing Machine (ECOTECH) and the Rubber Shredder Machine (DIANYAN; ECOTECH). The Wire Drawing Machine plays a crucial role in tire recycling, with its primary function serving as extracting steel wires from used or scrap tires. This operation typically occurs during tire segmentation and processing, facilitating the separation of steel wires from other materials, thereby streamlining the recycling and reuse.

The second critical component of waste tire pre-treatment is the Rubber Shredder Machine, an ingenious mechanical apparatus designed to shred and recycle the rubber materials, which is structured to minimise rubber waste into smaller fragments, thereby simplifying its management and process for recycling endeavours. The fundamental role of the rubber shredder is to classify the tire elements for segregated processing. In terms of the post-shredding, this machine ensures the effective separation of fibre products and rubber components in tires. This categorisation streamlines the recycling process, which enables more efficient recovery of the valuable materials present in each tire.

Table 7
Materials Component of passenger car and truck tires.

Composition	Passenger car tire	Truck tire
Natural rubber	22%	30%
Synthetic rubber	23%	15%
Carbon black	28%	20%
Other additives (e.g. curing agents, textiles)	14%	10%
Steel	13%	25%
Estimated average weight of new tire	8.5 kg	65 kg

5.2. Recycling of steel wires

The raw material of RSF in this study is recycled steel wires. After the wires are separated from the tires with Wire Drawing Machine, the Wire Forming Machine is used to make metal wires into specific shapes by bending, coiling, shaping, cutting, and joining wires into desired shapes to meet different industrial and manufacturing needs.

In addition to using steel wire from waste tires as steel fibre, recasting is also a common recycling method. However, this recycling category tends to consume a large amount of fuels. According to Björkman and Samuelsson (2014), the benchmark CO_2 emissions from the basic oxygen and electric furnace routes are about 1770 and 380 kg CO_2 per ton liquid steel, respectively. Meanwhile, the benchmark total energy consumption is about 4900 and 1100 kWh per ton of liquid steel, respectively. Compared to remanufacturing, the simple processing and utilisation of existing materials improves the recycling cost while saving manpower, material resources and time.

5.3. Recycling of waste rubber

According to described by Formela (2021), rubber represents a significant portion of tire composition, being the most abundant material. Specifically, it comprises 46% of car tires and 45% of truck tires. Such significant waste rubber composition opens up a broader recycling possibilities than the relatively limited options for scrap steel recycling (Khaloo et al., 2008). Furthermore, Table 8 outlines and juxtaposes various prevalent rubber recycling techniques, encapsulating their respective merits and drawbacks. Therefore, with the insights from this comparison, several strategies should be discerned to capitalise on the waste rubber derived from discarded tires.

5.4. Recycling of waste textile

Compared to steel and other wastes, the proportion of fibre in tires is very small but should not be ignored. Table 8 summarises several commonly used fabric recycling methods, which compares their advantages and disadvantages.

5.5. Sustainable Evaluation of waste tires

The existing reviews regarding the recycling methods of waste tires can be compiled in Table 9, which concisely presents greenhouse gas (GHG) emissions associated with each method. The summary provides a clearer overview of the environmental impact of each recycling approach, which helps make more sustainable decisions in waste tire management in circular economy.

While the economic benefits of tire recycling, such as the unquantifiable the value of utilising waste rubber in playground construction, may not be readily apparent, it is crucial to accentuate the practice's

Table 8
Evaluation of rubber recycling method and textile recycling method.

Methods	GHG Emission kg/CO_2 kg	Cost Benefit $/kg	Advantage	Disadvantage
Renew the rubber of Tires and Shoes	+0.434(Fiksel et al., 2011)	–	Environmental-friendly Energy-saving Resource Efficiency	Cost Quality Toxic Emissions
Remark Conclusion: According to the table above, waste rubber can be utilized to create rubber shoe soles and tire treads, which can reduce the demand for new rubber, thereby improving resource utilisation. However, it is important to address the environmental impact of the recycling process. However, despite the disadvantages mentioned above, waste tires still generate a large amount of sewage and toxic gases. Therefore, it is worth noting that while the method does not reduce the price of rubber products much, meaning that the environmental advantages might outweigh this limitation. Another challenge associated with this recycling method coems from controlling the quality of recycled rubber products. Furthermore, the uneven types of recycled rubber make it challenging to ensure strict control over the final product quality. Therefore, the lack of uniformity not only affects the overall product quality but also hinders significant price reductions in rubber products.				
Creating high-energy fuel	−0.613(Fiksel et al., 2011)		High Economic Value Energy-saving	Emissions Infrastructure Maintenance Inefficiency
Remark Conclusion: As a flammable material with a high calorific value, rubber can be potentially utilized as a fuel, thereby reducing the reliance on fossil fuels effectively (Araujo-Morera et al., 2021). However, it is important to consider the environmental impact associated with burning rubber. However, the combustion process releases a significant amount of toxic gases, which needs a high infrastructure standard. Therefore, special equipment and experienced personnel are essential for safe and efficient operation.				
Cement Production	−0.543(Fiksel et al., 2011)		Energy-saving Higher Cement Quality	Toxic Emissions Infrastructure Maintenance
Remark Conclusion: The high calorific value of waste rubber presents a significant energy efficiency, making it a valuable supplement or potential replacement of traditional fossil fuels during cement preparation (Williams, 2013). Such practice can potentially reduce the overall cost of cement production. Moreover, incorporating waste rubber into the cement mixture can even enhance the final product durability. However, there are significant challenges when using rubber as a substitute of traditional fossil fuels because the rubber combustion generates toxic emissions, which requires strict pollution control measures. Furthermore, the quality of the fuel derived from waste rubber may vary, which can influence the stability of cement production. In addition, specialised facilities and equipment are required to effectively control the burning of waste rubber and prevent toxic gas leakage, which are crucial to ensure the safety and environmental sustainability of utilising rubber as a fuel source in the cement industry.				
Methods	GHG Emission kg/CO_2 kg eq	Cost Benefit $/kg	Advantage	Disadvantage
Produce insulation materials Make industrial fabrics	−8 (Zamani et al., 2015)	0.5–0.6 (Mäkelä et al., 2020)	Waste Reduction Cost Benefit	Quality Control Pre-treatment
Remark Conclusion: The excellent thermal properties of various fibres make fibre-based insulation a popular option to enhance energy efficiency and reduce heating or cooling costs in buildings (Neri et al., 2023). Compared to the conventional insulation production, conversing waste fibres into insulation typically requires less energy, which thereby further reduces the associated carbon footprint (Landi et al., 2018). However, notable drawbacks should be considered in addition to the benefits. The quality and properties of insulation derived from waste fibres can vary significantly depending on the fibre types. Therefore, it is crucial to address the potential health hazards associated with certain waste fibres, especially those with undergone chemical or dyeing treatments. Therefore, a proper treatment before insulation is vital to ensure the safety of occupants. Moreover, durability is considered another concern because fibre-based insulation may not be as its resilient as traditional alternatives. Furthermore, the collection, sorting, and cleaning processes involved the preparation process before recycling are complex and expensive, which adds to the overall costs of fibre-based insulation.				

Table 8 (*continued*)

Methods	GHG Emission kg/CO_2 kg eq	Cost Benefit $/kg	Advantage	Disadvantage
Polyester Recycled	−0.9 (Zamani et al., 2015)	0.85 (Mäkelä et al., 2020)	High Economic Value Energy-saving Environmental-Friendly	Emissions Quality Control Chemical Pollution
Remark Conclusion: The waste polyester fibre recycling offers several environmental benefits, including the natural resource conservation of oil, which reduces the demand for raw materials and the environmental pressure. Furthermore, polyester recycling consumes less energy than virgin polyester production, which is energy-saving and reduces greenhouse gas emissions. From the business perspective, using the recycled polyester can provide advantages in costs, contributing to price stability and overall cost efficiency. However, certain challenges are associated with recycled polyester. Therefore, different qualities compared to virgin polyester may arise, which potentially leads to the reduced strength or colour changes. To ensure the efficient recycling, the proper sorting and cleaning of waste polyester fibres are crucial because the contamination by dyes or other fiber types can affect the quality and purity of recycled polyester. In addition, some recycling processes for polyester may involve chemicals that pose potential hazards to the environment and human health. Therefore, it is essential to employ environmentally friendly and safe recycling methods to mitigate negative impact.				
Energy Recovery:	−0.23 (Zamani et al., 2015)	–	Energy-saving Cost Benefit	Air Pollution
Remark Conclusion: Recycled waste fibres can serve as a valuable energy source, which reduces waste volumes and helps reduce greenhouse gas emissions. However, air pollution can occur during incineration, economic viability, technical innovation, and potential competition with recycling efforts.				

importance in the circular economy. This study focuses on the waste rubber and RSF recycling to assess economic worth. According to Table 9, which summarises the cost benefit and GHG emission of each recycling methods, the pre-treatment machine is only considered the electricity consumption in the cost benefit analysis, which is 0.046kw and 0.03 kwh when recycling 1 kg tires. From the analysis of waste rubber recycling, the power generation efficiency of rubber is evaluated, which determines the equivalent amount of electricity corresponding to the energy produced by consuming 1 kg of rubber before evaluating the economic value of waste rubber power generation relative to it. According to Mungyeko Bisulandu and Marias (2023), the heat reaction of tires is −1296.3 kJ/kg, which can generate 0.36 kwh/kg of electricity. The RSF multiplies the cost (0.4$/kg) by 1.5 times, which juxtaposes with the prevailing market ISF prices (2.2$/kg (Qin and Kaewunruen, 2022)). Since the electricity price on the GlobalPetrolPrices website is 0.15$/kwh, this method offers a realistic estimate of the economic value intrinsic to recycling these materials. Furthermore, these assessments underscore the significant economic potential of waste material recycling, reinforcing the viability of tire recycling in the circular economy. Comparing the GHG emissions associated with the recycling of various secondary materials, the recycling of RSF may not have the highest emissions reduction. However, the cost-effectiveness of RSF cannot be ignored, as it is saving a value of $1.6 per kilogram. This can significantly decrease construction costs without compromising the structural integrity of the project.

Upon comprehensively analysing and evaluating each criterion, the overall potential of recycling waste tires can be determined, as depicted in Table 9. While the economic value derived from recycling waste tires seems to be insignificant, the practice does not detract from its substantial impact on reducing greenhouse gas emissions. Besides, even with the least efficient recycling methods, waste tire recycling can still contribute to significantly reducing emissions (Wu et al., 2021). When it comes to assessing the recycling value, the recycling of ordinary passenger car tires can yield an economic value of $3.19 per tire, while heavy truck tires can generate a value of $32.92. According to the analyses, given that nearly 1.5 billion tires are replaced annually, recycling ordinary tires can result in an economic value of $\$ 4.8 \times 10^9$ and

Table 9
summarised the Materials Component, GHG emissions and Cost Benefit.

	GHG Emission kg/CO_2 kg eq	Cost Benefit $/kg	Ref.
Pre-Treatment for Tire/kg			
Tire Wire Drawing Machine	0.011	−0.0017	(ECOTECH)
Tire Shredder Machine	0.007	−0.0011	(DIANYAN; ECOTECH)
Steel Recycling/kg			
Recycled Steel Fibre	0.07	1.6	(Qin and Kaewunruen, 2022)
Rubber Recycling/kg			
Cement Production	−0.543	0.054	(Fiksel et al., 2011)
Creating High-Energy Fuel	−0.613	0.054	
Renew the Rubber	0.434	–	
Textile Recycling/kg			
Energy Recovery	−0.23	–	(Mäkelä et al., 2020; Zamani et al., 2015)
Producing insulation materials	−8	0.5–0.6	
Making industrial fabrics	−8	0.5–0.6	
Polyester Recycling	−0.9	0.85	
Remark Conclusion			
Tire Type	**Passenger car tire**	**Truck tire**	
GHG Emission CO_2 kg eq/pre tire	−11.9–1.84	−67.62–13.51	
Cost Benefit $/pre tire	2.60–3.19	30.65–32.92	

mitigate greenhouse gas emissions by 17.85×10^9 CO_2 kg eq. In addition, a typical tree can absorb around 21 kg of carbon dioxide annually (Boiler). Remarkably, CO_2 emission of this recycling method is equal to the volume that 85 million trees can absorb over a decade. Additionally, the economic value of recycling is comparable to the value derived from 67 million barrels of oil. Therefore, these findings underscore the immense environmental and economic potential of waste tire recycling, which amplifies its role in advancing towards a sustainable circular economy.

6. Conclusion

Since laboratory tests of the mechanical properties and dynamic properties of ISFs have shown a gradual increase in the concrete properties with the addition of fibres, this study focuses on evaluating the possibility of using RSFs as a substitute in ISF-FRC. Therefore, sseven concrete mixes with different fibre substitution ratios have been designed and subjected to various experimental tests, including compressive and splitting tensile strength, CMOD, and Modal Tests. According to the comparative analysis of RSF and ISF concrete, including the exploration of their microstructure, the following conclusions can be drawn:

Initially, although there is limited performance of concrete improved by a higher RSF proportion, RSF concrete can effectively improve the performance of concrete when the RSF content is below 0.8%. Regarding the effect of RSF fibres, using 1.2% of these fibres can increase the compressive strength, splitting strength, and flexural strength of the concrete by 11.2%, 32.5%, and 82.3% of plain concrete, respectively.

By analysing the tensile test results, it can be seen that RSF has an obvious shortage in improving the residual stress of concrete compared to ISF because of the defects in the RSF manufacturing technology. While the RSF hook end suffer from high fatigue damage, the reduction of the hook end strength can lead to a decrease in its ability to restrict large cracks, which will reduce the mechanical properties of the fibre reinforced concrete.

The results show that with increasing RSF fibre content, the natural frequency of concrete increases slightly from 1343.0Hz of plain concrete to 1385.9Hz with fibre content of 1.2%, about 3.19% increasement. Similarly, the natural frequencies of ISF concrete beams also increase with the increasing fibre content from up to 1.2% natural frequency to over 2.62%. In addition, by combining the natural frequency in the dynamic concrete performance with the mechanical concrete performance, a precise potential relationship between them can be observed. According to Fig. 6, the corresponding mechanical concrete properties corresponding to the solid-state frequency can be obtained, with the predictive index R^2 above 0.97. Therefore, this study can provide a corresponding theoretical basis for future non-destructive testing, which makes a comparative evaluation of existing structures.

Lastly, as a recyclable material, RSF's contribution to the environment and circular economy cannot be ignored. Therefore, this paper focuses on the comprehensive evaluation and analysis of tire recycling. According to the findings, recycling a car tire and a truck tire can respectively reduce GHG emissions of 11.9 CO_2 kg eq/pc and 67.62 CO_2 kg eq/pc. In addition, the economic benefits in the tire recycling process cannot be neglected, in which recycling a truck tire can earn $32.92 per tire. Furthermore, the recycling of steel wires from tires for manufacturing RSF provided the highest recycling value compared to other secondary materials.

CRediT authorship contribution statement

Xia Qin: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Xu Huang:** Conceptualization, Data curation, Investigation, Validation, Visualization, Writing – original draft. **Sakdirat Kaewunruen:** Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Writing – review & editing.

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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