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Investigating the effect of green hybrid fibre on toughening and mechanical properties of iron-tailing sand concrete

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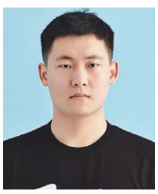

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Professional paper

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To improve the brittleness and susceptibility to cracking of iron tailings sand concrete, fibre blending was employed to toughen and resist cracking in the material. In this study, two inexpensive and environmentally friendly fibre materials were used: recycled tire steel fibre (RTSF) and coconut fibre (CF). The two fibre materials were blended and the resulting mixture was subjected to a series of performance tests, including compressive, tensile, flexural, impact, and bending tests. The effects of the fibre doping method and amount on the toughness and mechanical properties of iron tailings sand concrete were investigated in terms of the law of effect of the blended fibre admixture on the toughness and mechanical properties of iron tailings sand concrete. The results show that adding two types of fibres can effectively improve the toughness and mechanical properties of the specimen, and the hybrid fibre has a more obvious effect. Compared with the blank control group (Non), the compressive strength, splitting tensile strength, bending strength, impact strength, and bending peak load of the concrete with 0.75 % RTSF and 0.2 % CF increased by 20.8 %, 42.9 %, 40.4 %, 92.4 %, and 37.5 %, respectively. Combined with the theory and fracture surface morphology analysis, it was shown that recycled tire steel fibres play a major role in cracking resistance, while coconut fibres play a toughening role.

Key words:
fibre blending, recycling tire steel fibre, coconut fibre, iron tailing sand, toughening

Stručni rad

Huawang Shi, Zhenyao Shi, Bo Zhang, Huilin Chen

Istraživanje utjecaja zelenih hibridnih vlakana na žilavost i mehanička svojstva betona od pijeska željezne jalovine

Kako bi se smanjila krtost i mogućnost stvaranja pukotina u betonu s pijeskom željezne jalovine, upotrijebljena je mješavina vlakana. U ovome su radu primijenjene dvije vrste jeftinih i ekološki prihvatljivih vlakana: čelična vlakna od recikliranih guma (RTSF) i kokosova vlakna (CF). Vlakna su pomiješana te je dobivena mješavina koja je podvrgnuta nizu ispitivanja, uključujući tlačno ispitivanje, vlačno ispitivanje, ispitivanje savijanjem i ispitivanje udarom. Učinci metode dodavanja vlakana i njihova udjela na žilavost i mehanička svojstva betona od pijeska željezne jalovine istraženi su u smislu ovisnosti utjecaja dodatka mješavine vlakana na žilavost i mehanička svojstva betona. Rezultati pokazuju da dodavanje dviju vrsta vlakana može učinkovito poboljšati žilavost i mehanička svojstva uzorka, a hibridno vlakno ima izraženiji učinak. U usporedbi s referentnom skupinom (Non) tlačna čvrstoća, vlačna čvrstoća cijepanjem, čvrstoća na savijanje, udarna čvrstoća i vršno opterećenje na savijanje betona s udjelom od 0,75 % RTSF-a i 0,2 % CF-a povećali su se redom za 20,8 %, 42,9 %, 40,4 %, 92,4 % te 37,5 %. U kombinaciji s teorijskom analizom i analizom morfologije površine loma pokazalo se da čelična vlakna od recikliranih guma igraju glavnu ulogu u otpornosti na stvaranje pukotina, dok kokosova vlakna utječu na žilavost betona.

Ključne riječi:
mješavina vlakana, čelična vlakna od reciklirane gume, kokosova vlakna, pijesak željezne jalovine, žilavost

1. Introduction

Iron tailings are the waste or by-products produced in the process of mining and contain impurities in the ore; the residue that fails to extract the valuable metal and the waste after the ore has been processed by milling, beneficiation, etc., and a large amount of stockpile will encroach on the land resources and cause environmental pollution. In recent years, it has been found that iron tailings sand can be used to prepare concrete for solid waste reuse and reduce resource waste [1-3]. A substantial body of research [4-12] has demonstrated that the optimal replacement rate of iron tailing sand in concrete can enhance its strength. However, exceeding this rate may negatively affect the cracking performance of the concrete. The incorporation of fibres can enhance the toughness and cracking performance of concrete, and thus, they can be combined with iron tailing sand to enhance the toughness and cracking performance of iron tailing sand concrete [13-16].
Research [17] has shown that steel fibres mixed in iron tailings sand concrete can inhibit the development of cracks, reduce the width of cracks, toughen and resist cracks, and significantly improve the mechanical properties of iron tailings sand concrete within a certain admixture range. Scholars at home and abroad have found that recycled tire steel fibres (RTSF) can be used in concrete materials, and the mechanical properties of concrete have a certain role in improving the cost of industrial steel fibres (ISFs). Karsamarakoon et al. also tested the mechanical properties of RTSF and compared them with those of SF and found that the compressive strength of concrete after adding RTSF increased by 7-12 %, and the compressive strength of concrete after adding SF increased by 17-20 % [18]. Hang [19] investigated the uniaxial tensile stress-strain (σ-ε) relationship; it was found that RTSF only weakly increased the tensile strength of SFRC when the fibre admixture was low. Carrillo [20] found experimentally that RTSF and ISF were similar in enhancing the compressive strength, modulus of elasticity, and Poisson's ratio of concrete specimens, and that RTSF improved the toughness of concrete; however, the contribution of RTSF was lower than that of ISF. Fan et al. [21] demonstrated that RTSF could markedly enhance the fundamental mechanical characteristics of concrete and could substitute industrial ISF within a specified dosage range.
However, a single type of fibre has limitations and cannot adequately improve the performance of concrete; the addition of a variety of fibres to the design of concrete can significantly optimise the performance of single fibre concrete. Coconut fibre (CF) is a fibrous material extracted from the husk of coconut with light weight and good strength. Sivakumaresa Chockalingam, [22] used coconut fibre to reinforce high performance concrete and found that coconut fibre could improve the strength and durability of the concrete. Alomayri Thamer et al. [23] prepared concrete by simultaneously mixing several treated wastes, namely granulated blast furnace slag (GBFS), recycled coarse aggregate (RCA), and coconut fibre (CF). It was found that the mechanical properties of the reclaimed aggregate concrete modified by GBFS, CF, and the modified plasticiser were equal to or higher than those of the unmodified natural aggregate concrete. This indicates that the incorporation of CF can offset the negative effects of RCA on concrete to a certain extent. Studies have shown that adding coconut fibres to concrete increases its cracking resistance and improves its toughness and impact resistance [24-26]. The use of coconut fibres helps to reduce the generation of waste and has a low environmental impact. Coconut fibres are a renewable resource, and the utilisation of coconut fibres as a fibre reinforcement for concrete is in accordance with the tenets of sustainable development and serves to diminish the necessity for traditional nonrenewable fibre materials.
Therefore, this study investigates the toughening and crack-resistance effects of recycled tire steel-coconut hybrid fibres on iron tailings sand concrete through compressive tests, splitting tensile tests, impact resistance tests, and bending performance tests, providing a reference for providing green hybrid fibre-reinforced concrete materials as well as the application and promotion of iron tailings sand concrete in actual projects.

2. Experiment

2.1. Experimental materials

2.1.1. Cementing materials

The test employs ordinary silicate cement of P-O42.5. The cement complies with GB 175-2023 "General Silicate Cement" [27]. Class I fly ash. Its technical indicators meet the national standard GB/ T159-2017 "Fly ash for cement and concrete" [28].

2.1.2. Coarse and fine aggregates

The fine aggregate was selected from iron tailings sand, which was sourced from the Chengde area in Hebei, China. This was configured as Zone II medium sand with a fineness modulus of 2.8

Table 1. Aggregate physical properties

Properties / Aggregate	Apparent density [kg/m³]	Bulk density [kg/m³]	Water absorption [%]	Mud content [%]	Crushing index	Aggregate size range [mm]
Crushed stone	2758.5	1531.5	0.58	0.52	9.6	2.5 – 20
Iron tailing sand	2732	1506	6.5	2.6	10.1	0 – 9.5

following screening. Coarse aggregate from the Handan City quarry natural gravel, with a continuous particle size gradation of 5–20 mm. The grading curves of the aggregates are shown in Figure 1. The physical properties of the aggregates are shown in Table 1.

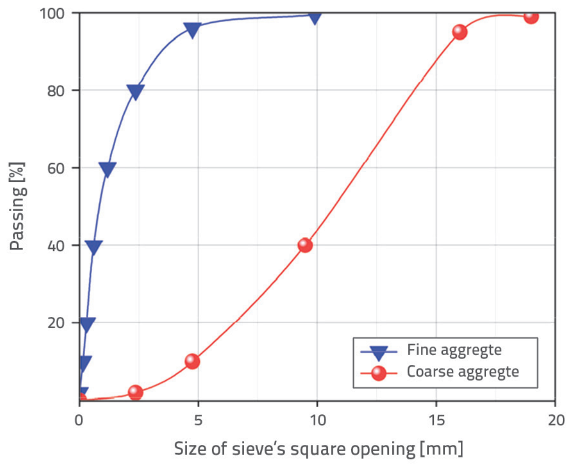

Figure 1. Grading curves of the aggregate

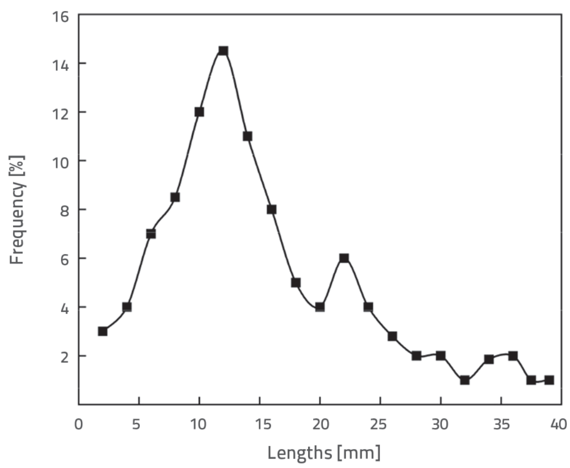

Figure 2. RTSF length distribution frequency diagram

2.1.3. Fibres and their treatment

Two types of fibres, i.e., Recycled Tire Steel Fibre (RTSF) and Coconut Fibre (CF). RTSF was taken from Xingtai Waste Tire Treatment Plant. RTSF needs to be processed by standard sieve sieving in order to filter the rubber particles contained therein. The RTSF length distribution frequency diagram is shown in Figure 2. After processing is seen in Figure 3. CF was extracted from discarded coconut shells, after which it was first subjected to a soaking process to reduce the deposit. After air drying, the CF was divided into individual filaments and sheared to a length of 10 mm (Figure 3), after which the coconut fibre was soaked in a NaOH solution with a mass fraction of 5 % for 5 h [29], washed, air-dried, and then stored. The principal performance characteristics of the fibres are presented in Table 2.

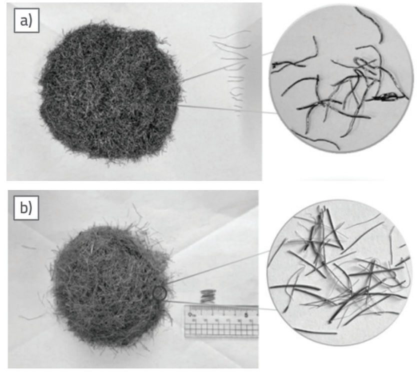

Figure 3. Recycled tire steel fibre and coir fibre appearance: a) RTSF; b) CF

Table 2. Main performance parameters of RTSF and CF fibres

Fibre / Properties	RTSF	CF
Density [g·cm³]	7800	1150
Tensile strength [MPa]	2185	95~230
Diameter [μm]	210~240	100~450
Length [mm]	2.9~39.8	10

2.1.4. Water and water-reducing agent

Water was procured from laboratory tap water. The water-reducing agent was a high-efficiency polycarboxylic acid water-reducing agent with a water reduction rate of 25 %. By using a polycarboxylic acid water-reducing agent, the ionic adsorption of the fibre itself could be changed, and simultaneously, the consistency of the cement mortar could be adjusted, thus dispersing the fibres [25] and avoiding fibre agglomeration.

2.2. Mixing ratio and specimen preparation

In this experiment, the water-cement ratio was set to 0.38; the fly ash dosage was 20 %; the sand rate was 35 %; two fibre dosages were taken as the experimental variables; the volume dosage of RTSF was selected to be 0.5 %, 0.75 %, and 1.0 %; the volume dosage of coir fibre was selected to be 0.1 %, 0.2 %, and 0.3 %; the control group was taken; a total of 16 groups of tests were set up; and the coordination ratio of each group is shown in Table 3.

The concrete preparation process is shown in Figure 4. The concrete was mixed with reference to CECS 13:2009 "Standard Test Methods for Fiber Concrete" [30]. First, iron tailings sand, cement, and fly ash were put into the concrete mixer for dry mixing for 2 min, after which coarse aggregate was added and then dry mixed for 3 min; coconut fibre was sieved into the coconut fibre using a standard sieve; water and water-reducing agent were added; the mixture was subjected to a mixing period of four minutes; and the same standard sieve was used to sieve

Table 3. Recycled Tire Steel-Coconut blended fibre iron tailings sand concrete ratio

<table>
<tr><th>Group</th><th>Water [kg/m³]</th><th>Cement [kg/m³]</th><th>Fly ash [kg/m³]</th><th>Iron tailing sand [kg/m³]</th><th>Crushed stone [kg/m³]</th><th>Water reducing agent [kg/m³]</th><th>RTSF [kg/m³]</th><th>CF [kg/m³]</th></tr>
<tr><td>Non</td><td rowspan="16">170</td><td rowspan="16">358</td><td rowspan="16">89</td><td rowspan="16">624</td><td rowspan="16">1159</td><td rowspan="16">3.6</td><td>0</td><td>0</td></tr>
<tr><td>RS0-C01</td><td>0</td><td>1.15</td></tr>
<tr><td>RS0-C02</td><td>0</td><td>2.3</td></tr>
<tr><td>RS0-C03</td><td>0</td><td>3.45</td></tr>
<tr><td>RS05-C0</td><td>39</td><td>0</td></tr>
<tr><td>RS075-C0</td><td>5.5</td><td>0</td></tr>
<tr><td>RS10-C0</td><td>78</td><td>0</td></tr>
<tr><td>RS05-C01</td><td>39</td><td>1.15</td></tr>
<tr><td>RS05-C02</td><td>39</td><td>2.3</td></tr>
<tr><td>RS05-C03</td><td>39</td><td>3.45</td></tr>
<tr><td>RS075-C01</td><td>58.5</td><td>1.15</td></tr>
<tr><td>RS075-C02</td><td>58.5</td><td>2.3</td></tr>
<tr><td>RS075-C03</td><td>58.5</td><td>3.45</td></tr>
<tr><td>RS10-C01</td><td>78</td><td>1.15</td></tr>
<tr><td>RS10-C02</td><td>78</td><td>2.3</td></tr>
<tr><td>RS10-C03</td><td>78</td><td>3.45</td></tr>
</table>

the RTSF. A fresh concrete mix with good fluidity was obtained after mixing, and its slump was measured to be approximately 95–150 mm. It was then poured into a 100 mm cube and a 100 × 100 × 400 mm prism-shaped mould. All the samples were compacted and shaken for 30 s on a concrete shaking table and then covered with plastic wrap. After being placed at room temperature for 24 h, the demolded sample was placed in a standard curing room for 28 d, and then tested.

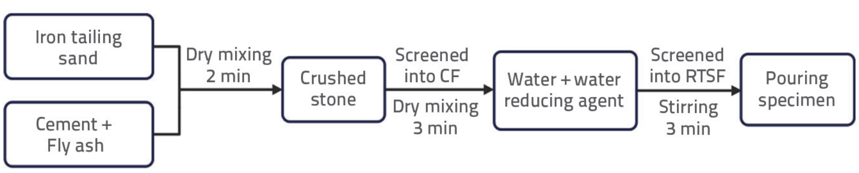

Figure 4. Flowchart of concrete preparation

2.3. Test methods

2.3.1. Compressive strength, split tensile test, and flexural strength test

The specimen was tested after 28 d of curing in standard conditions, with reference to "Standard Test Methods for Mechanical Properties of Ordinary Concrete" (GB/T 50081-2002) [31]. A YE-2000A microcomputer-controlled automatic pressure tester was selected to carry out compressive and splitting tensile strength tests on the 100 ×100 ×100 mm cube specimen with a loading rate of 0.5 MPa/s and 0.05 MPa/s. Three specimens were tested in each group, and the resulting average value was

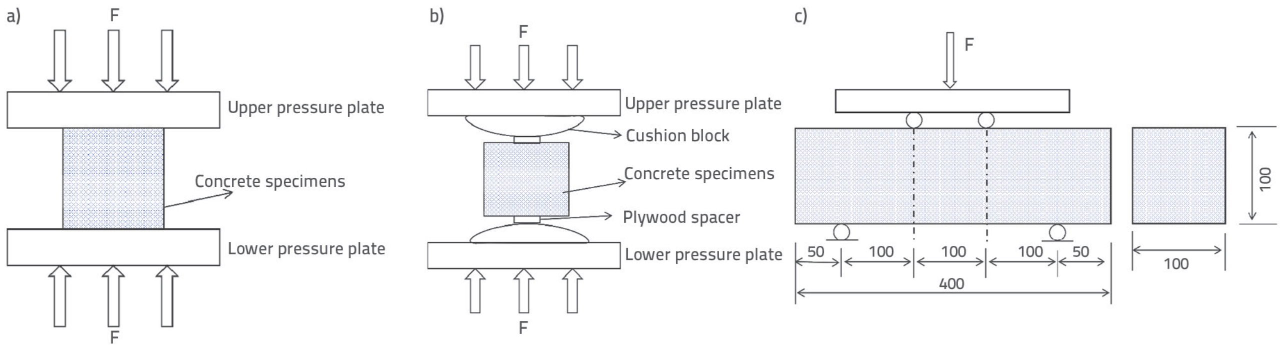

Figure 5. Schematic diagram of experimental loading: a) Schematic loading diagram of compressive test; b) Schematic loading diagram of splitting tensile test; c) Schematic loading diagram of flexural test

taken for the compressive and splitting tensile strength of the group. For the 100 × 100 × 400 mm prismatic specimen block used in the flexural strength test, the loading rate was 0.05 MPa/s. The flexural strength of each group was determined by testing four specimens and calculating the mean value. The experimental loading schematic is shown in Figure 5.

2.3.2. Impact resistance test

The impact strength was determined by the falling ball method [32]. A steel ball of 100 mm diameter and 3.5 kg mass was selected and dropped freely from a height of 1 m to the centre of the test block, and the impact was repeated until a visible crack appeared on the surface of the test block. The number of impacts was recorded and converted to impact energy in order to determine the impact strength of iron tailing sand concrete. The impact strength was determined by calculating the mean value of three specimens tested in each group. The experimental loading schematic is shown in Figure 6.

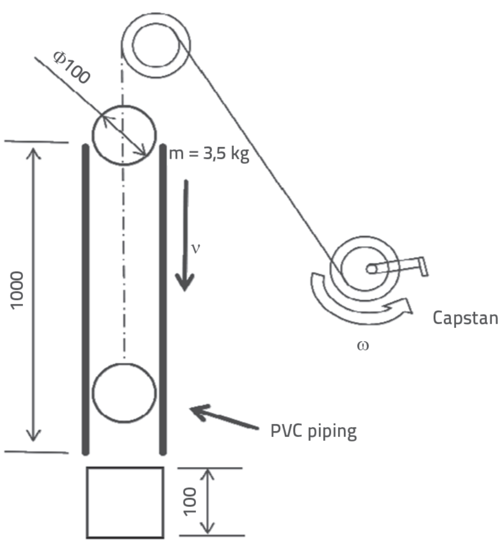

Figure 6. Schematic diagram of impact resistance test, specimen 100 x 100 x 100 mm

The results were calculated using equation (1):

$$W = n \cdot m \cdot g \cdot h \quad (1)$$

where *W* is the impact strength of the material, in N-m; *n* is the destruction of the specimen impact number; *m* is the mass of the falling hammer, in kg; *g* is the acceleration of gravity, taken as 9.8 N/kg; and *h* is the vertical drop height of the falling hammer.

2.3.3. Flexural toughness test

Specimens were cured to 28 d age for the test, according to CECS 13:2009 "Standard Test Methods for Fiber Concrete" [30] specimens in the WDW-100D electronic universal testing machine for loading, using a displacement meter to measure mid-span disturbance; and the mean value was calculated as the result of testing four specimens in each group, using displacement control for loading and a loading speed of 0.5 mm/min. A schematic of the experimental loading is shown in Figure 7.

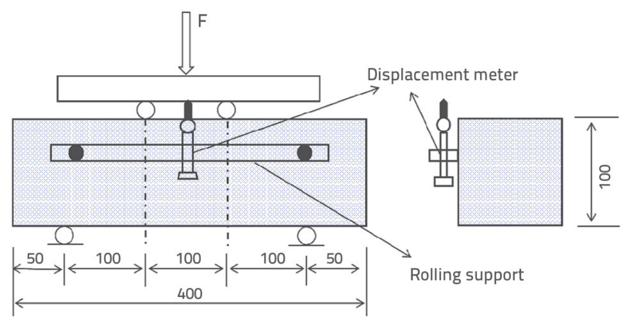

Figure 7. Flexural toughness test, specimen 100 x 100 x 400 mm

3. Test results and discussion

3.1. Mechanical properties

Compressive strength, tensile splitting, and four-point flexural testing of mechanical properties.

3.1.1. Compressive strength

The compressive strength values of the mixed fibre iron tailings sand concrete are shown in Figure 8. The addition of 0.5 % and 0.75 % RTSF increased the compressive strength of iron tailings concrete to 53.64 MPa and 54.24 MPa, respectively, which is about 10.12 % and 11.35 % higher, respectively, than that of the control group (48.71 MPa). This is slightly different from the results reported by Baricevic et al., which may have been caused by the different distribution frequencies of the studied RTSF lengths. The length of the RTSF used in this experiment was longer, concentrated at approximately 10 mm, whereas the length of the RTSF used by Baricevic et al. was concentrated at approximately 6 mm. The shorter the fibre, the easier it is for clumping to occur in the concrete, thus reducing the compressive strength of the concrete [33]. The RTSF is distributed in a chaotic phase inside the concrete and can effectively absorb energy to inhibit the initial cracking of the concrete. Therefore, the compressive strength of the iron tailings sand concrete increased after the addition of RTSF. However, when the RTSF content ranged from 0.75 % to 1.0 %, there was no significant increase in the compressive strength value of the concrete (52.81 MPa), especially when the RTSF content reached 1.0 %, which showed a small decrease in the compressive strength value compared to the dosing of the 0.75 % group. This may be because the fibre dosage was too high, and it was easy to produce a fibre agglomeration effect in the concrete, resulting in the destruction of the overall uniform structure of the concrete. Each part of the force deformation was inconsistent, which led to a reduction in its compressive strength.

In a certain mixing range of RTSF, mixing with CF can significantly improve the compressive strength of iron tailings sand concrete, and single mixing with 0.2 % of CF can enhance the compressive strength of iron tailings sand concrete by approximately 7.72 %. When the amount of CF mixing is more than 0.2 %, the degree of improvement in compressive strength appears to be a small reduction in the degree of compressive strength. Thus, when the amount of CF was 0.2 %, the best effect of the improvement in the compressive strength of concrete was observed. Similar to RTSF, CF exhibits a three-dimensional chaotic phase distribution system in concrete, absorbing the energy of external work and forces, and inhibiting the generation of small cracks [34].

The mixing of 0.1-0.2 % CF and 0.75 % RTSF can maximize the compressive strength of iron tailing sand concrete. For example, the compressive strength of RS075-C01 is 58.07 MPa, and that of RS075-C02 is 58.86 MPa, which is 19.22 % and 20.84 % higher, respectively, than that of the control group (Non). These results indicate that a mixed admixture of RTSF and CF can form a good structural crack-resistant system in concrete [35], that delays the generation of microscopic cracks and the transition to the development of macroscopic cracks.

3.1.2. Splitting tensile strength

The splitting tensile strengths of the mixed-fibre iron tailings sand concrete are presented in Figure 9. The splitting tensile strength of the iron tailings sand concrete exhibits a notable enhancement with the incorporation of RTSF. In the range of 0.5 to 1.0 % of the RTSF admixture, the split tensile strength of the iron tailings sand concrete increases by 10.9 to 19.6 % compared with the control group. In comparison with RTSF, CF also demonstrates a notable enhancement in the splitting tensile strength of concrete, although to a lesser extent. The splitting tensile strength of the iron tailings sand concrete mixed with 0.2 % CF exhibits an improvement of approximately 9 % compared with that of the Non group. This is because of the low tensile strength and modulus of elasticity of CF, which limit its role in the tensile strength of concrete. However, it is a more environmentally friendly and economically viable option, and it also helps improve the cracking resistance of iron-tailing sand concrete.

Compared with the mono-doped RTSF and CF, the positive mixing effect of the two fibre mixtures was better. For example, the splitting tensile strength of the RS075-C02 group was 4.46 MPa, which was 43 % higher than that of the control group (Non), and higher than that

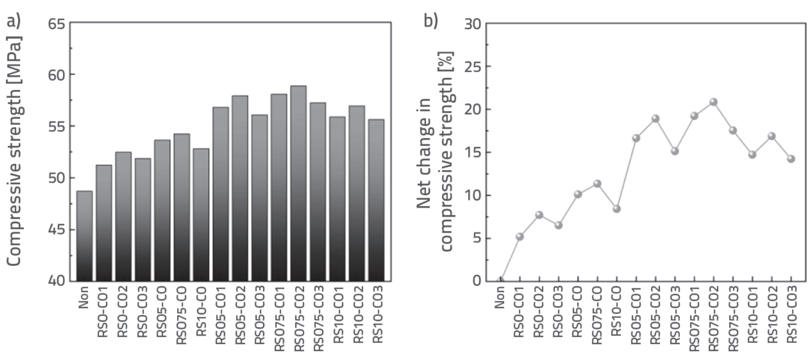

Figure 8. Compression test results: a) Compressive strength; b) Net change in compressive strength

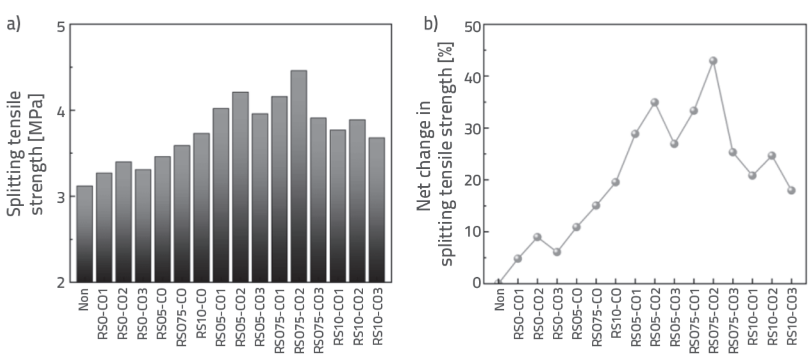

Figure 9. Split tensile test results: a) Split tensile value; b) Net change in split tensile strength

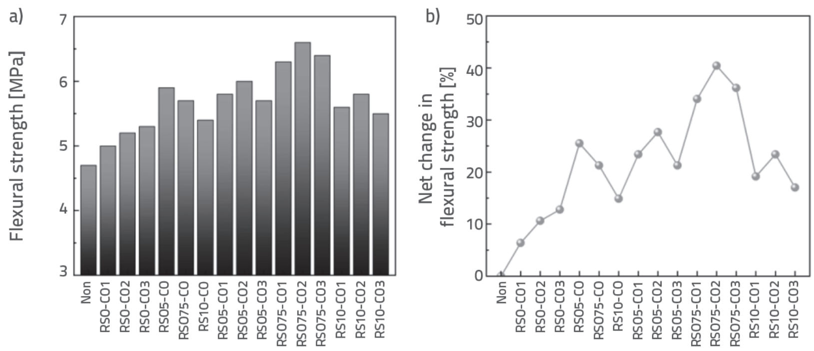

Figure 10. Four-point flexural strength test results: a) Flexural strength; b) Net change in flexural strength

of the single-doped RTSF group (15.1 %) and the single-doped CF group (9 %). Other hybrid fibre groups also showed some degree of improvement over the single fibre groups. In other hybrid fibre concrete matrices, such as steel-polypropylene hybrid fibre concrete, also exists in this fibre synergistic effect; hybrid fibre system of high modulus of elasticity and low modulus of elasticity of fibres intermingled with each other to form a similar "Crown of tree" structure in the concrete matrix. The high modulus of elasticity fibre is like a "central branch"; the low modulus of elasticity fibre plays the role of "side branch".

3.1.3. Flexural strength at four points

The flexural strength values of the mixed fibre iron tailings sand concrete are presented in Figure 10. The maximum increase in flexural strength of specimens in single mixed CF and RTSF groups is 12.8 % (RS0-C03) and 25.5 % (RS05-C0), respectively, and the bending strength values are 5.3 MPa and 5.9 MPa, respectively. The effect on flexural strength of concrete is most significant when the volume mixing amount of RTSF reaches 0.5 %. This is consistent with the results of Gu et al. [36]. The most significant effect of RTSF on the flexural strength of concrete is due to the fact that compared with CF, RTSF has higher elastic strength and better resistance to macro-cracking and bridging cracks. In the flexural process of the specimens, fibres are pulled out from the concrete matrix and consume part of the energy; therefore, the addition of a certain amount of RTSF and CF can significantly improve the flexural properties of concrete. In addition, the RTSF contains rubber particles that are not adequately screened out and rubber micropowder attached to its surface, which weakens the adhesion stress between the concrete interior and the aggregate and cementitious materials. Consequently, an increase in the RTSF dosage results in a corresponding reduction in the flexural strength of the concrete, owing to the formation of weaker interfaces within the material.

3.2. Toughness evaluation

3.2.1. Impact strength analysis

Impact energy (Figure11) and Tension-to-compression ratio (Figure 12) present the results of the impact strength test on specimens with varying fibre groups. As illustrated in the figures, the data demonstrate that the impact energy of the specimens in each group was enhanced to varying degrees following the incorporation of fibres. Notably, the mixed-fibre group exhibits superior impact resistance. This is mainly because the specimen in the impact force, the fibres inside the concrete and the concrete matrix at the same time deformation consumption of energy, thus improving the impact strength of the specimen (resistance to initial cracking strength); in the specimen by the impact of the destruction of the specimen, across the specimen to destroy the crack interface of the fibres, to play

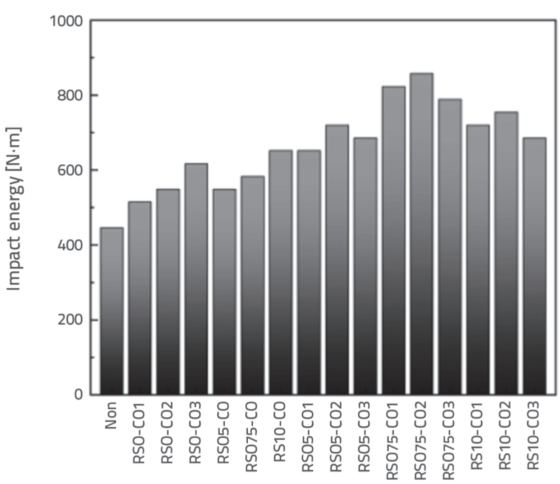

Figure11. Impact energy

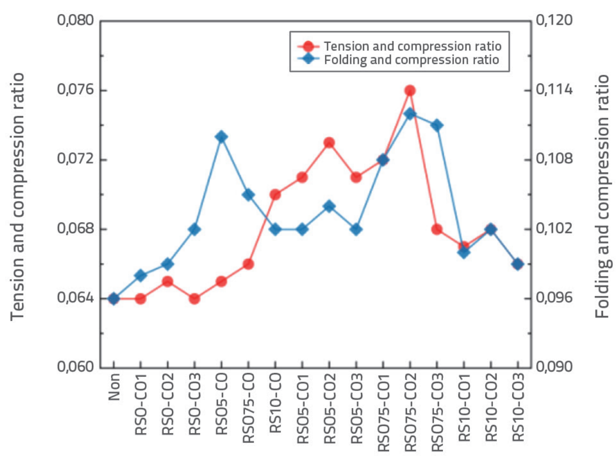

Figure 12. Tension-to-compression ratio and folding ratio

the role of the "bridging", to prevent the further development of cracks, and improve the impact strength of the specimen. After the specimen was damaged by impact, the fibres across the interface of the damaged cracks of the specimen played the role of "bridging", preventing the further development of cracks and improving the impact resistance of the specimen. The experimental results indicate that the impact strength of the single-mixed CF and RTSF groups is comparable, the impact strength of CF specimen with 0.3 % volume content is 617 N·m, and the impact strength of RTSF specimen with 1.0 % volume content is 652 N·m. This is similar to the straw fibre studied by Zhang Xueyuan et al. [37] because CF, as a plant fibre, has a high cellulose content and good flexibility, which can effectively absorb and disperse external impact forces, thus improving the impact resistance of concrete specimens.

3.2.2. Analysis of tensile and compression ratio and folding ratio

The tensile compression ratio refers to the deformation capacity of concrete under tensile and compressive stresses. The folding ratio refers to the performance of the concrete under repeated stretching and compression. These two ratios can be used as indices to evaluate the toughness of concrete. This is shown in Figure 11. and Figure 12. The tensile-compression ratio of the specimens first increases and then decreases with the increase of CF admixture, and first increases and then gradually flattens out with the increase of RTSF admixture. Compared with the Non group and the single fibre group, the tensile ratios of the blended fibre group were substantially improved. The tensile ratios of the RS05-C02 and RS075-C02 groups were improved by 14 % and 19 %, respectively, compared with the Non group, indicating that the RTSF and CF blending can show a good positive blending effect and improve the tensile ratio of concrete. With an increase in CF mixing, the trend of the specimen's flexural compression ratio shows a gradual increase because when the CF mixing is constant, the reduction in its flexural strength is less than the compressive strength, and the addition of CF improves the flexural performance of the specimen. With the increase of RTSF dosage, the trend of the specimen's flexural compression ratio shows a gradual decrease, and the flexural compression ratio of the RS05-C0 group is higher than that of the other single-doped fibre groups, which is due to the fact that when the volume dosage of RTSF is 0.5 %, the degree of its flexural strength is much greater than its compressive strength. Combined with a comprehensive analysis of the tensile and folding compression ratios of each group of specimens, both the single-mixed fibre group and the mixed fibre group can improve the toughness of the specimens within a certain mixing amount, which can effectively improve the brittle iron tailings and concrete defects.

3.2.3. Flexural toughness (and flexural toughness index)

The flexural toughness of each specimen was quantified by the area under the load-displacement curve during bending. A larger area indicates a superior flexural toughness of the specimen [38]. The load-displacement curves of the specimens in the Mono-doped fibre group and the Blended fibre group are presented in Figure 13 and in Figure 14.

As can be seen from Figure 13, the load-displacement curves of the specimens in each group are almost similar before reaching the peak load. The non-group specimens show a futile decrease in the curves after the peak load without a delayed descending section, and the specimens show sudden brittle damage, which indicates that the specimens exhibit poor flexural toughness in the bending process. The peak loads of the specimens in the single-doped CF group are higher than those of the Non group, and after the peak load, there is a short delayed descent section, which is delayed with an increase in CF doping, but fails when the displacement reaches approximately 3 mm; the doping of CF causes delayed destruction of the specimens. Thus, the doping of CF improved the flexural toughness of the specimens to a certain extent. The flexural toughness curve of the specimen in the single-doped RTSF group shows an obvious delayed decline, and the decline in the toughness curve is gentler with an increase in RTSF doping. Doping of the RTSF from 0.5 % to 1.0 % results in a continuous reduction in the peak load, accompanied by a more pronounced flattening of the decreasing section of the toughness curve. This indicates that an excessive RTSF can further enhance the flexural toughness of the specimens, although it will have an unfavourable effect on their mechanical properties. This is because, following the attainment of the peak load, the damage state of the specimen underwent a gradual transition from internal to macrocracks. The RTSF then transmitted stress through cracks within the matrix, thereby acting as a crack-bridging agent. Consequently, when cracking occurred after the attainment of the peak load, the specimen was still capable of withstanding a portion of the load [39] until the RTSF was extracted from the interior of the specimen matrix.

As illustrated in Figure 14 when the RTSF doping is confirmed, the peak load of the specimen belonging to the mixed fibre group exhibits a pattern of gradual increase followed by a decline. This

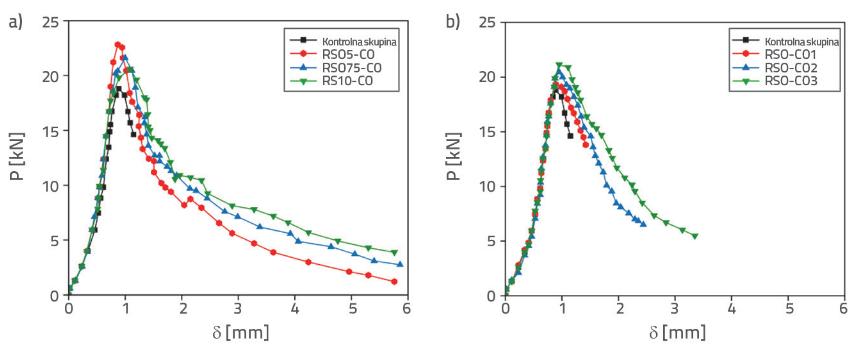

Figure 13. Load-displacement (P-δ) curves of single-doped fibre group: a) Single-doped recycled tire steel fibre; b) Single-doped coconut fibre

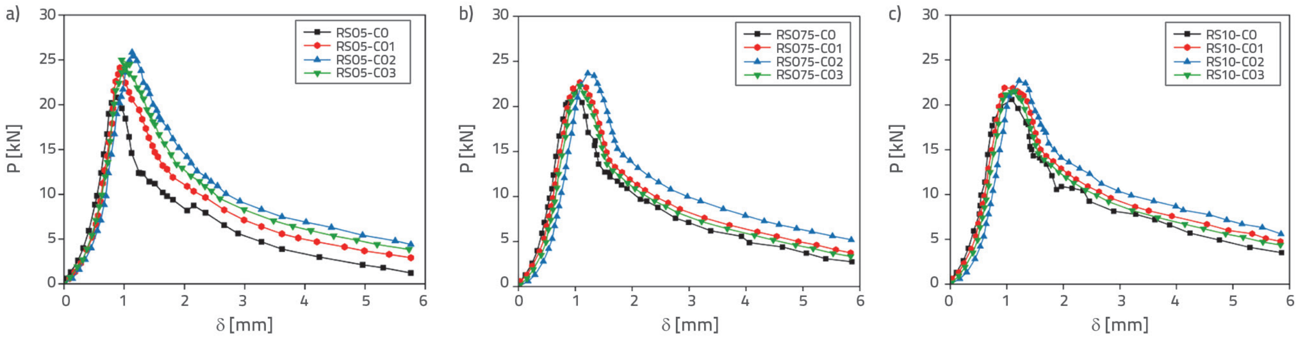

Figure 14. Load-displacement (P-δ) curves for hybrid fibre groups: a) P-δ curve of recycled tire steel fibre 0.5 %; b) P-δ curve of recycled tire steel fibre 0.75 %; c) P-δcurve of recycled tire steel fibre 1.0 %

phenomenon can be attributed to the fact that the incorporation of CF enhances the cracking resistance and toughness of the specimen. However, with an increase in the volume doping of CF, there are too many fibres inside the specimen matrix, which leads to the uneven dispersion of fibres, which in turn affects the densification and strength of the specimen [40], and the peak load of the specimen decreases.

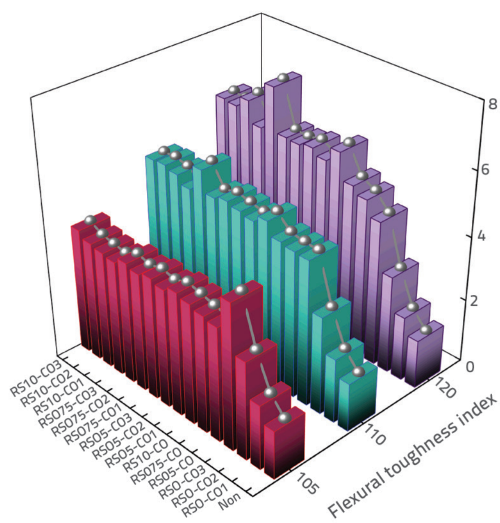

Figure 15. Flexural toughness index

When the CF doping is 0.2 % and the RTSF doping is 0.75 %, the peak load of the specimens increases by 37.5 % compared with that of the non-doped group. Overall, the peak load enhancement of the specimens in the mixed fibre group is more pronounced, and the decreasing section of the load-displacement curve is more gradual. Furthermore, the enhancement effect on the flexural toughness of the specimens in the mixed-fibre group is more pronounced.

The bending toughness index of concrete, as calculated according to CECS 13:2009, "Standard of Test Methods for Fiber-Reinforced Concrete", is illustrated in Figure 15. The relevant specific data are shown in Table 4. The bending toughness index (I5, I10, and I20) of the Non group is 1.52, while that of RS0-C01, RS0-C02, and RS0-C03 is 1.3, 2.0, and 3.0 times that of the Non group, respectively. The flexural toughness index increases with the CF and RTSF volumes. However, the RTSF group demonstrates superior ductility compared with the CF group. This is attributed to the inherent strength and capacity of RTSF to bridge concrete cracks, which effectively delays the process of bending and breaking concrete, thereby enhancing its brittleness. The bending toughness index (I5, I10, and I20) of RS075-C02 is 2.5, 3.6, and 4.7 times that of the Non group, respectively.

3.3. Analysis of toughening and crack-resisting mechanism

With reference to the energy balance theory, the damage process of concrete, the fibre morphology of the fracture surface of concrete beams, and the toughening and crack-resisting mechanism of hybrid fibres on iron tailing sand concrete were analysed [41].

Table 4. Flexural toughness index of various specimens

Group	I5	I10	I20	Group	I5	I10	I20
Non	1.52	1.52	1.52	RS05-C02	3.71	4.93	5.81
RS0-C01	2.02	2.02	2.02	RS05-C03	3.82	5.02	5.72
RS0-C02	3.07	3.07	3.07	RS075-C01	3.71	4.91	5.75
RS0-C03	4.56	4.56	4.56	RS075-C02	3.82	5.56	7.10
RS05-C0	3.58	4.59	5.03	RS075-C03	3.62	4.78	5.69
RS075-C0	3.66	4.66	5.25	RS10-C01	3.68	5.03	6.28
RS10-C0	3.77	5.06	6.06	RS10-C02	3.75	5.13	6.02
RS05-C01	3.81	4.84	5.62	RS10-C03	3.95	5.09	6.07

From the perspective of energy balance, when hybrid fibre concrete is cracked under force, the work done by the external force Gw is equal to the sum of the energy absorbed by the concrete matrix Gj and the energy absorbed by the fibres Gx. The energy absorbed by the matrix includes the strain energy generated by the deformation of the matrix itself, Gjy, the absorbed energy of plastic deformation at the tip of the crack, Gjl, and the absorbed energy of the cracked extension surface, Gjk. The energy absorbed by the fibres includes the energy absorbed by the fibres themselves, Gx, and the energy absorbed by the fracture, Gx. The energy absorbed by the fibre includes the energy absorbed by the fibre itself, Gxd, and the debonding energy between the fibre and the matrix, Gxj, and the energy balance of the cracking process is shown in equation (2).

$$Gw = Gj + Gx = Gjx + Gjl + Gjk + Gxd + Gxj \quad (2)$$

During the loading of the fibre concrete, microcracks began to form within the matrix. At this stage, the fibres surrounding these microcracks absorbed the energy associated with matrix cracking, transforming it into strain energy within the fibres. This process inhibited the propagation of concrete cracking. Schematic diagram of mixed fibre iron tailing sand concrete for crack resistance shows the schematic diagram of the cracking resistance of mixed fibre iron tailing sand concrete; when the external force reaches the ultimate load of the specimen, the specimen will crack at the weaker position in the span. After the ultimate load was reached, the specimen cracked, and the loading continued; the cracks continued to extend in the weaker places inside the specimen matrix, bypassing the parts where the fibres were well distributed and uniform. Single-doped fibre group specimen cracking performance for vertical upward cracking, while the hybrid fibre group, due to the existence of the positive mixing effect between the fibres and the distribution of the denser, can absorb the energy is also relatively more, the crack inhibition effect is better, the cracks are shown as a curved upward extension, as shown in Figure 17. In the process of crack extension, the matrix and fibre as the main body of the deformation can be co-deformed; at this time, the external force to perform the work by the matrix and fibre together; crack extension to the fibre near the surface of the matrix crack extension of the absorbed energy is transferred to the fibre; at this time, the load by the fibres and the bond between the matrix to bear; and when the matrix fractures, the fracture part of the matrix is no longer able to assume the role of the external load, and the load is borne entirely by the fibre, which is the main part of the crack. The load is borne by the fibre through its own strain to absorb energy and then prevent the specimen cracks from extending.

The damaged surface of the concrete beam after the specimen was damaged is shown in Figure 18. It can be observed that in the fracture plane of the specimen, there are obvious traces of "pulling out" of RTSF, which indicates that the specimen in the process of stress damage, RTSF sliding in the substrate, when the macroscopic cracks appeared and expanded, the RTSF in the crack due to the high modulus of elasticity and strength, to withstand the main stress, and along with the friction between RTSF and the substrate to absorb a lot of energy, effectively slowing down the further expansion and extension of the specimen cracks. Along with the friction between the RTSF and the matrix, a large amount of energy is absorbed, which effectively slows down further expansion and extension of the crack in

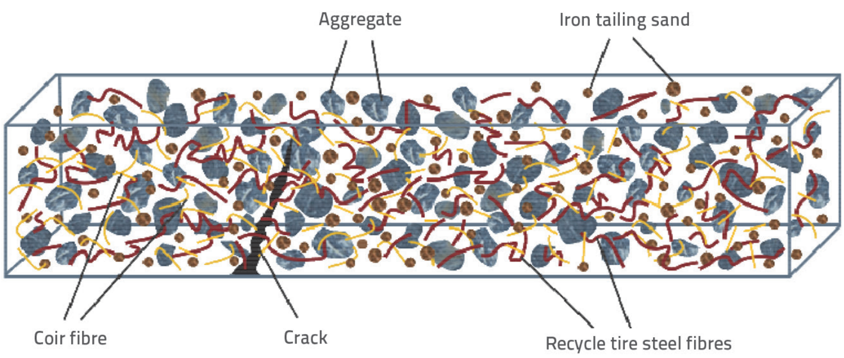

Figure 16. Schematic diagram of mixed fibre iron tailings sand concrete for crack resistance

Figure 17. Damage pattern of fibre concrete beam specimens and fibre distribution at fracture

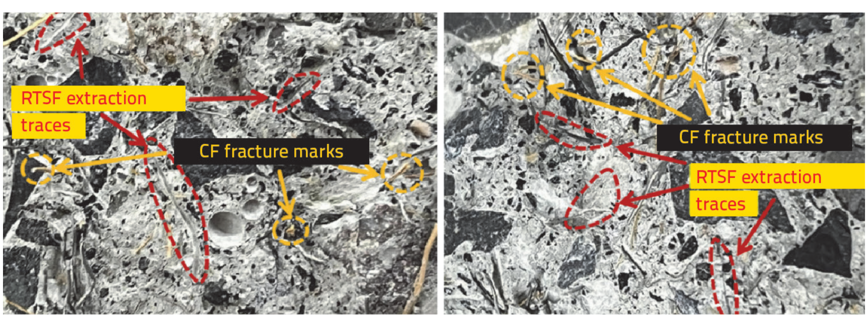

Figure 18. Fibre morphology of fracture surfaces of concrete beams

the specimen, and the RTSF plays an obvious crack-blocking role in this process. With the further expansion of the crack, the RTSF continued to slide and was then distributed in the RTSF around the CF owing to the low modulus of elasticity and strength. The first to fracture, as shown in Figure 18. Fibre morphology of fracture surfaces of concrete beams, as can be clearly seen in the CF force, was "torn" traces. In this process, the CF absorbed a lot of energy [42], and to a certain extent delayed the further stretching of RTSF, hindered the generation of matrix micro-cracks and the expansion of macro-cracks, and played an obvious role in toughening. Thus, it can be seen that the two hybrid fibres play a synergistic role in iron tailing sand concrete [43], inhibiting the generation and expansion of internal cracks in the matrix to different degrees, and improving the toughness and mechanical properties of iron tailing sand concrete.

4. Conclusion

The present study aimed to investigate and compare the effects of RTSF, CF admixture, and the admixture method on the toughening and mechanical properties of iron tailings sand concrete experimentally, and the following conclusions were drawn:
The incorporation of recycled tire steel and coconut fibres into iron tailings sand concrete can enhance its mechanical properties. The addition of 0.75 % recycled tire steel fibres and 0.2 % coconut fibres was found to have the most beneficial effect on the mechanical properties of the iron tailings sand concrete; the compressive strength of the concrete group with 0.75 % RTSF and 0.2 % CF increased by 20.8 % compared with the control group. The splitting tensile and bending strengths increased by 43 % and 40.4 %, respectively. All these values were higher than those of the mono-doped fibre group and the other mixed groups.
The toughness of iron-tailing sand concrete was further enhanced by varying the quantities of recycled tire steel and coconut fibres. At a dosage of 0.75 % recycled tire steel fibre and 0.2 % coir fibre, the tensile and compression ratios of the specimens reached a maximum, and the toughness index exhibited a positive correlation with an increase in the two types of fibre mixing. The impact strength was the highest at this dosage, representing a 92.4 % increase compared with that of the control group.
The peak load in the bending of the specimen was enhanced to a certain extent by both the single-doped fibre group and the mixed-fibre group, as evidenced by the increased area under the load-displacement curve. However, the load-displacement curve of the specimen in the mixed-fibre group exhibited a more gradual decline, suggesting a more pronounced improvement.
The RTSF and CF play distinct roles in the reinforcement of iron-tailing sand concrete. The RTSF enhances the initial cracking strength of iron tailings sand concrete owing to its high strength and modulus of elasticity, which inhibits the generation and extension of new cracks. In contrast, CF fibres enhance the toughness of iron-tailings sand concrete because of their low modulus of elasticity and good ductility. Once the two fibres were combined, they acted in concert with the cement matrix, impeding the formation and propagation of cracks within the iron tailings sand concrete to varying degrees. This resulted in the enhanced toughness and mechanical properties of the iron-tailing sand concrete.

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