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Experimental Study On Flexural Toughness Of Hybrid Fiber Recycled Concrete Based On A Circular Plate Method

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Abstract
The flexural toughness of concrete is pivotal for its structural integrity and longevity, prompting recent interest in enhancing it through fiber incorporation. Hybrid fiber recycled concrete (HFRC) merges recycled materials with fiber reinforcement, offering a promising avenue for improvement. This study investigates HFRC's flexural toughness using the circular plate method, providing a detailed examination of hybrid fibre's impact on its mechanical properties and behavior.
Seven groups of circular plate specimens were meticulously crafted for flexural toughness tests, comprising recycled aggregates and hybrid fibers with varying types, dosages, and admixture methods. Flexural tests, conducted under quasi-static loading conditions, assessed HFRC's bending performance and crack resistance using a universal testing machine. The study aimed to analyse how recycled coarse aggregate and hybrid fibers influence HFRC's damage pattern, alongside investigating the effects of steel fiber admixture, type, and polypropylene fiber dosage on its flexural toughness and post-peak plastic deformation capacity.
Experimental findings shed light on HFRC's flexural behavior, showing varying levels of toughness and crack control among specimens with different fiber types. Notably, HFRC reinforced with ultra-short microfilament steel fibers (SF1) outperformed those with multi-anchored steel fibers (SF2). Optimal bending performance occurred at 1.2% SF1 dosage and 0.11% polypropylene fiber dosage, enhancing mechanical properties and crack resistance. These results underscore hybrid fibre's efficacy in bolstering HFRC's flexural performance, offering sustainable construction solutions. Insights gained aid in material optimization and design strategies, fostering advancements in infrastructure development and green building practices.
Keywords: *Steel-polypropylene hybrid fiber; Recycled concrete; Flexural toughness; Circular plate method; Energy absorption value*

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I. Introduction

For half a century, recycled concrete has been widely used in civil engineering fields such as bridges and roads, housing construction, and foundation engineering because of its advantages of being green, environmentally friendly, and fitting into the national sustainable development strategy[1][2] . However, the low tensile strength, toughness, and ductility of recycled concrete improve the performance of recycled concrete. Research shows that the addition of steel fiber materials to form steel fiber recycled concrete is an effective way [3], [4][5]. However, recycled concrete is a multi-layered, multi-component non-homogeneous mixed material, which makes the level of reinforcement and toughening of a single steel fiber limited [6]. Suppose the recycled concrete is mixed with an appropriate amount of high modulus steel fibers and low modulus polypropylene fibers to form steel-polypropylene hybrid fiber recycled concrete (Hybrid fiber recycled concrete, HFRC). In that case, the two fibers can stimulate each other at different levels of the structure and different stages of loading to complement the "1+1>2" fiber hybrid superposition effect [7][8][9][9][10][11][12], which can significantly improve the bending performance of single-mixed steel fiber recycled concrete and improve its post-cracking deformation performance.

Currently, scholars in China and abroad are working on the hybrid fiber concrete flexural toughness, carried out a series of studies, and achieved important research results. Related studies have been conducted to consider the effects of steel fiber admixture, polypropylene fiber admixture, fiber mixing method, fiber arrangement and the effect of dry and wet cycles of sulfate on flexural toughness[13][14][15] [16] . Meanwhile, Zhang et tal.[17] conducted four-point flexural toughness tests on 16 sets of fiber-recycled concrete beam specimens and investigated the effect law of steel-polypropylene hybrid fibers on the flexural toughness of recycled concrete beams with different admixture methods and fiber admixture amounts [17]; Su Jun et al [18] investigated the effect of different recycled coarse aggregate replacement rates and two different fiber admixtures on the bending performance of steel-PVA hybrid fiber recycled concrete beams by conducting four-point bending tests on 18 sets of fiber recycled concrete prism specimens[19]. The above study mainly adopts beam-type specimens to test the flexural toughness of hybrid fiber recycled concrete, but HFRC is often used in actual engineering applications in the form of slab-like members, and there are large differences between the bending mechanism of beam-type specimens and that of recycled concrete in engineering, and the test results are relatively discrete and cannot illustrate the three-dimensional toughening effect of hybrid fiber. Therefore, compared with the beam method using beam specimens, the circular plate method in the Standard for Fiber Concrete Test Methods (CECS13: 2009) [20] can reflect the flexural toughness of HFRC more objectively.

Because of this, the flexural toughness test of HFRC based on the circular plate method is carried out in this article to analyze the effects of three factors, namely, volume admixture of steel fiber, steel fiber type and polypropylene fiber, on the compressive strength and flexural toughness of HFRC respectively, and to discuss the mechanism of toughening and crack resistance of HFRC based on the energy-deflection curve, and to give the optimal fiber admixture for the flexural toughness of HFRC.

II. Materials And Methods

Materials

Cement: Huaxin brand ordinary silicate cement with a grade of 42.5 was used [17]. Fine Aggregates: Medium-coarse River sand with a fineness modulus of 2.8. Natural Coarse Aggregates: Continuously graded aggregates ranging from 5 to 16.5 mm. Recycled Coarse Aggregates: Obtained from waste concrete blocks from a demolition area in an urban village in Wuhan. These aggregates were processed through manual primary crushing, machine re-crushing, and manual screening to achieve the same grain size and gradation as natural coarse aggregates. Mineral Powder: S95 grade blast furnace slag powder. Water Reducing Agent: Polyhydroxy acid high-performance water-reducing agent with a 20% water reduction rate. Water: Ordinary tap water. Fibers: Ultra-short microfilament steel fibers, multi-anchored steel fibers, and "Dura" brand polypropylene fibers produced by Hill Corporation of the United States.

III. Methods

Concrete Mix Preparation:

The baseline mix ratio for C50 concrete was configured as shown in Table 1. Seven different fiber mix forms were designed for this study. One group of plain concrete specimens and six groups of recycled concrete specimens, incorporating 50% recycled coarse aggregate replacement, were prepared. The fiber properties and volume admixture for each group is detailed in Table 2 and Table 3 respectively. Circular slab specimens and cubic specimens were fabricated for each mixed group. The recycled coarse aggregates were processed to ensure uniformity in grain size and gradation, matching the specifications of natural coarse aggregates.

Mixing Process, Casting, Curing and specimen maintenance of recycled concrete.

The concrete mixtures were prepared by initially dry mixing the cement, fine aggregates, natural coarse aggregates, and recycled coarse aggregates. Subsequently, the fibers were added according to the designed mix forms, ensuring even distribution throughout the mix. The polycarboxylic acid high-performance water-reducing agent was then introduced, followed by the gradual addition of water to achieve the desired workability as mentioned in the previous studies [17] . The recycled concrete mixing process used in this experiment is the Two-stage mixing approach (TSMA) as used by the previous studies by Mandal R et al [20]. Using 100L double horizontal forced mixer, firstly pour the recycled coarse aggregate into the mixer to pre-mix for 1min, then add natural coarse aggregate and sand to continue mixing for 2mins; Then add half of the total quantity of water used and continue mixing for 3mins; Add cement and blast furnace slag powder and continue mixing for 3mins; After that, while mixing the mixture, evenly spread into the mixer successively steel fibers and polypropylene fibers pre-rolled by hand and continue to mix 6mins, so that the fibers and the matrix materials are fully mixed evenly; Finally, add the water reducing agent and the remaining water into the mixer one after another, and continue to mix for 3mins. The hybrid fiber recycled concrete mix prepared by the above-mentioned mixing process has good compatibility and fluidity, and no fiber agglomeration phenomenon occurs. The mixed concrete was cast into molds to form the circular slab and cubic specimens. The specimens were vibrated to remove any air bubbles and ensure compaction. After casting, the circular plate specimens were covered with plastic sheets to prevent moisture loss and were left to set for 24 hours. Post-setting, the circular plate specimens were demolded and cured in a water tank at 20°C ± 2°C for 28 days.

Cube compressive and flexural toughness test methods.

After the curing period, the specimens underwent flexural toughness testing using a circular plate method. This method involved subjecting the circular slab specimens to monotonic loading until failure, while the cubic specimens were tested for compressive strength. The load-deflection behavior and energy absorption capacity were recorded and analyzed to assess the flexural toughness of each concrete mix. The tests were based on the Standard for Test Methods for Fiber Concrete (CECS13:2009) [20] and the Standard for Physical and Mechanical Test Methods for Concrete (GB-T 50081-2019)[20][21] , and the specimens used for the cubic compressive test were cubes with 100 mm side lengths, three in each group; The loading equipment is 200 tons of digital display pressure testing machine, loading method using stress control, loading rate of 0.05Mpa/s. After the test, read the peak load on the testing machine and calculate the compressive strength, the cube compressive strength size reduction factor is taken as 0.9.

Flexural toughness circular plate method test using a diameter of 800mm, thickness of 75mm circular plate specimens, each group is also 3; loading equipment selected Jinan Hengruijin company production of 300 tons of electro-hydraulic servo-hydraulic testing machine.

Table 1: Baseline mix ratio (kg/m3)

Materials / Category	Cement	Sand	Coarse Aggregate		Blast furnace slag powder	Water	Additional water	Water Reducer
			Natural aggregates	Recycled aggregates				
Plain concrete	456	712.8	915.6	—	96.2	220	4.95	5.52
Recycled concrete	456	712.8	457.8	457.8	96.2	220	15.25	5.52

Table 2: Fiber parameters

Fiber types	Quantity /root	Tensile strength /MPa	Length /mm	Diameter /mm
Ultra-Short Microfilament Steel Fiber (SF1)	85000	2000	13	0.20
Multi-anchored steel fibers (SF2)	19800	1000	30	0.50
Polypropylene fiber (PPF)	3.3×10^7	276	12	0.03

Table 3: Volume admixture of fibers in each group

Specimen set	SF1 volume admixture/%	SF2 volume admixture/%	PPF volume admixture/%
SN1	0	0	0
SR2	0	0	0
SR3	0	0.8	0.11
SR4	1.2	0	0
SR5	0.8	0	0.11
SR6	1.2	0	0.11
SR7	0	1.2	0.11

Based on the circular plate method in the Standard for Testing Methods for Fiber Concrete (CECS13: 2009)[22], the test loading supports were improved to make the whole test force transmission path clearer and to ensure that the damage cracks appear near the angle bisector of the line connecting the two adjacent supports and the center of the plate, and to make it more convenient to take and place the circular plate specimens before and after the test. Before formal loading, let the loading head contact with the center of the upper surface of the circular plate specimen, and control the load at the loading head within 0.2kN at this time. To eliminate the vertical deformation error between the cylinder of the testing machine and the bearing table and the lateral deformation error between the bearing table and the three cylindrical ball-hinged supports, the test was controlled in two stages, both of which were loaded with equal displacement. Loading at a rate of 1 mm/min until the load on the circular plate specimen reaches 1 kN; After the load reaches 1 kN, the test is completed by loading at a rate of 3mm/min until its central deflection reaches 45mm. After the test, the load-deflection curves of each specimen group were made based on the data collected by the load and displacement sensors, and the experimental data were collected and analyzed to compare the performance of plain and fiber-reinforced recycled concrete. The effects of different fiber proportions and aggregate replacement ratios on the flexural properties were evaluated. Statistical methods were employed to ensure the reliability and validity of the results, highlighting the improvements in flexural toughness due to hybrid fiber reinforcement.

IV. Results and Discussions.

Effect of fibers on the compressive strength of recycled concrete.

The compressive strength values of the cubes are shown in Table 4. From Table 4, the compressive strength of the recycled concrete specimen SR2 with 50% recycled coarse aggregate replacement rate was reduced by 4.82% compared to the plain concrete specimen SN1; The compressive strength of the recycled concrete specimens SR3 to SR7 with fibers increased to different degrees compared to the control specimen SR2 without fibers, with a maximum increase of 17.76%; Compared with the HFRC mixed with SF2, the compressive strength of HFRC mixed with SF1 increased by 7%-9%; in addition, the effect of PPF incorporation on the compressive strength of HFRC was somewhat weak although it caused the compressive strength to decrease, but the decrease was only 1.52%.

Table 4: Compressive strength values of cubes in each group

Specimen set	Compressive strength/MPa
SN1	56.54
SR2	53.94
SR3	55.24
SR4	63.52
SR5	59.23
SR6	62.57
SR7	57.16

Flexural toughness, Flexural damage process and damage pattern of recycled concrete slabs.

Plain concrete slab without fiber mixing

As the test loading proceeded, when the deflection of the plain concrete specimen SN1 without fiber reached about 1.2mm, three small cracks appeared at the same time at the bottom of the plate, which rapidly expanded from the center to the edge, and after a few seconds the cracks at the bottom of the plate rapidly expanded to the top of the plate, with a loud bang, the circular plate split into three pieces and smashed to the bottom of the testing machine bearing platform [21]. The damage fracture surface of the plain concrete specimen SN1 without fiber is very flat, almost in the shape of "one", and the damage shows the characteristics of brittle damage, and the damage pattern is shown in Figure 1.

Recycled concrete slab without fiber mixing

The damage process of the recycled concrete specimen SR2 without fiber mixing is more similar to that of the plain concrete specimen SN1, except those three small cracks just appeared at the bottom of the slab, and the circular slab immediately split into three pieces and smashed into the bottom test machine bearing. The crack expansion rate of the specimen SR2 of recycled concrete without fiber mixing was much faster than that of the plain concrete slab SN1, its damage fracture surface was also very flat and showed brittle damage characteristics, and the damage pattern is shown in Figure 1. It can be seen that the substitution of 50% recycled coarse aggregate increased the initial defects such as low strength and large internal porosity of the specimens of recycled concrete without fiber mixing, which intensified its brittle damage process and made it show more obvious brittle damage characteristics than specimen SN1.

Hybrid fiber recycled concrete slab

Flexural toughness circular plate method test on HFRC specimen SR5, when the deflection of the center of the specimen reached about 1.6mm, three small initial cracks appeared at the bottom of the specimen almost simultaneously, and all of them were located near the angle parallels of the line connecting the two adjacent ball joint supports and the center point of the specimen; With the increase of deflection at the center of specimen SR5, the width of the crack at the bottom of the specimen gradually increased, and the crack gradually expanded from the bottom to the side of the specimen, during which the steel fibers were straightened and pulled out, the polypropylene fibers were stretched and broken, and the small recycled concrete slag falls onto the bearing platform of the testing machine; When the deflection of the center of specimen SR5 reached 30 mm, the crack extended to the top of the specimen; until the end of the test, the circular plate specimen SR5 was concave downward in the center and warped upward at the edges, but did not fracture completely and remained as a whole (see e.g. Figure. 1), showing good ductility. Based on the fiber spacing theory, it is easy to find that it is because the fibers span both sides of the crack, which plays a good bridging role [23], the bond stress between the fibers and the recycled concrete relieves the expansion of the crack and the stress concentration phenomenon at the tip of the crack, extending the time of damage of the specimen as observed by previous studies[17] [24][25]

The crack development was faster in HFRC specimen SR3 compared to HFRC specimen SR5, and the crack at the bottom of the specimen started to extend to the top when the central deflection reached 19 mm. The flexural damage process and morphology of specimen SR3 are more similar to that of specimen SR5, and the damage morphology is shown in Figure 1. The crack widths of HFRC specimen SR5 and HFRC specimen SR3 were measured at 9 different cracks along 3 radial cracks after the test, and the crack widths of specimen SR5 were compared with those of specimen SR3 by taking the average value. Therefore, the crack control capability of HFRC specimen SR5 was better than that of HFRC specimen SR3. D. Gao et al [26], noted that the modifications of cracks also illustrate the effect of fiber type on the crack patterns of HFRBAC. The inclusion of steel fiber into RBAC makes concrete generate a smaller width of major crack than that of hybrid fibers and polyolefin fiber. The specimens with steel fibers exhibit the multi-cracking property. Moreover, the polyolefin fiber exhibits poorer crack resistance to RBAC than the steel fiber and hybrid fibers[26]. The merits of hybrid fibers on the flexural behavior of HFRBAC could be elucidated based on Fig. 5h, Fig. 5i and Fig. 5j, in which the ability of crack control and deformation of HFRBAC are improved by hybrid fibers. It means that the hybrid fibers could resist the further propagation of macrocracks, as reported by Wang et al. and Zhang et al.[15], [27]. The bridging of the hybrid fibers prevents the formation of cracks, and increasing the volume fraction of the hybrid fibers reduces the width of the main crack, as shown in Fig. 6. The samples without fibers are broken into two parts.

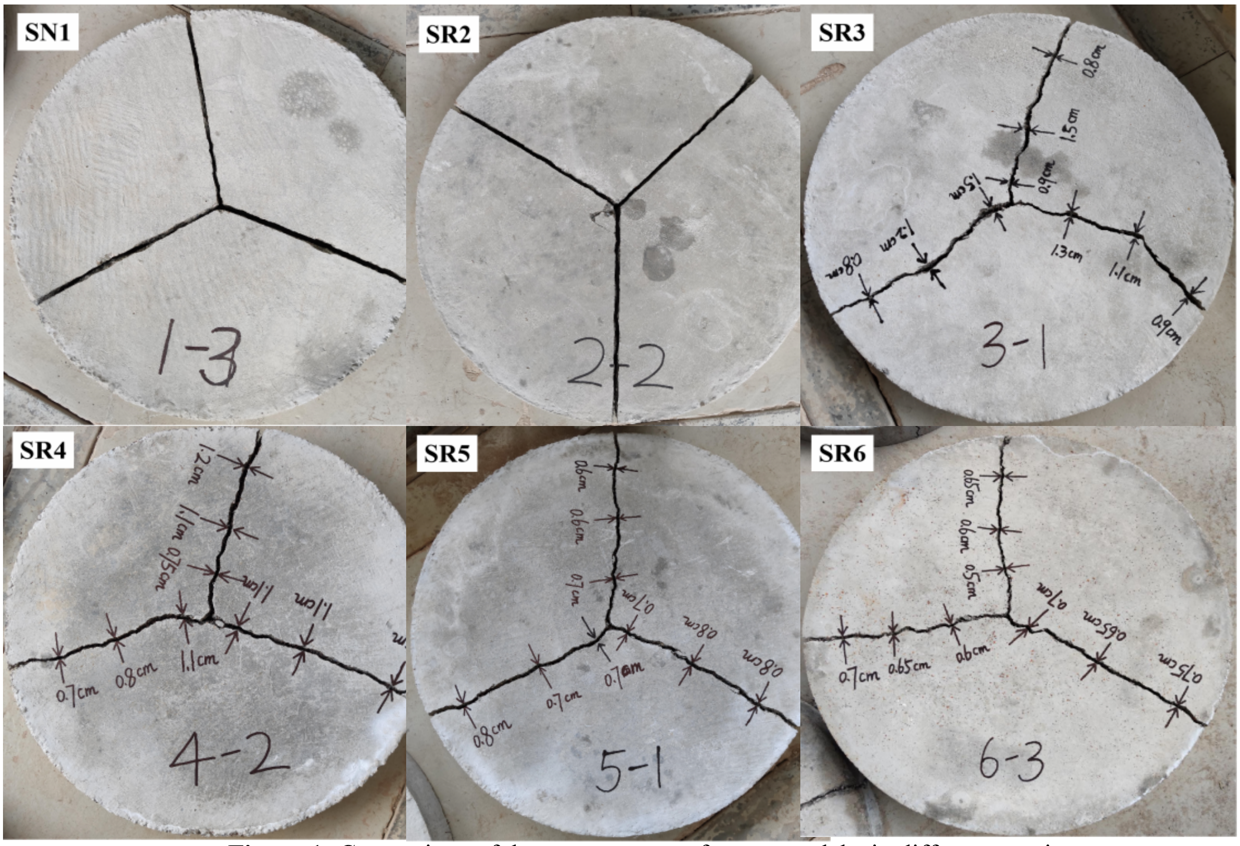

Figure 1: Comparison of damage patterns of concrete slabs in different specimen groups

Table 5 shows the crack width values of fiber recycled concrete slabs in different specimen groups, combined with Figure 1 and Table 5, the damage patterns of HFRC specimens SR3, SR5 and SR6 are more or less the same, all showing ductile damage characteristics; The recycled concrete specimen SR4 with single admixture of ultra-short microfilament steel fibers also showed ductile damage characteristics due to the bridging effect of steel fibers. The difference is that the specimen groups with different fiber volume admixture and mixing methods exhibited different crack control ability, which was ranked as SR6 > SR5 > SR4 > SR3.

Table 5: Crack widths of fiber recycled concrete slabs in different specimen group

Specimen set	Crack width value xi(i=1,2,3)/cm			Arithmetic mean of crack width X/cm
	Specimen1	Specimen2	Specimen3	
SR3	1.11	0.89	0.95	0.98
SR4	0.73	0.98	0.78	0.83
SR5	0.71	0.76	0.74	0.74
SR6	0.52	0.68	0.64	0.61

Load-deflection curves

Figure 2 shows the load-deflection curves of the recycled concrete samples SN1, SR2, SR3, SR5~SR7, where the pure concrete samples SN1 and SR2 without fiber mixture reached their respective initial crack loads when the mean deflection reached 1.2 mm and 1.0 mm , after that, the bending strength of the two groups of samples decreased sharply, and when the deflection values reached 3.87 mm and 3.21 mm, respectively, brittle instability damage occurred in both groups of samples; The damage process of the recycled concrete samples mixed with steel-polypropylene fibers is significantly expanded and can be divided into three stages using the HFRC sample SR6 as an example to study the bending state and fiber reinforcement mechanism of the recycled concrete slab with hybrid fibers in different stages.

(1) Elasticity stage: At the early loading stage, when the central deflection of the HFRC sample SR6 is small, as in section OA in Figure 2, the load-deflection curve of the HFRC sample SR6 overlaps with that of the control sample SR2 without fiber mixing, since the Deformation of the sample is small and the microcracks in the matrix do not extend the deformation of both the recycled concrete matrix and the hybrid fiber. The flexural properties of HFRC were not significantly different at this time, and the fibers had no significant influence on the flexural properties of the recycled concrete samples.

(2) Crack occurrence and expansion stage: As the load of the HFRC specimen SR6 continued to

increase, small cracks began to appear at the bottom of the specimen when the recycled concrete at the bottom of the specimen reached its initial crack tensile stress. At this point, the steel fibers at the ends of the crack can share some of the load by bridging. The polypropylene fibers near the microcrack can inhibit the stress concentration phenomenon at the crack tip and limit the further development of the crack [4], [28], [29], so that the stress does not decrease immediately after the sample cracks, but continues to increase as the deflection increases, it reaches the maximum bending stress (section AB in Fig. 2). HFRC exhibits significant work hardening properties at this stage.

(3) Crack-stable expansion and damage stage: The HFRC sample SR6 does not exhibit brittle instability damage immediately after the initial crack like the control sample SR2 without fiber mixture after reaching the peak bending load, but continues to be stressed by the bridging effect of the steel. Polypropylene hybrid fibers in the cross section of the crack (section BC in Fig. 2). As the load on the HFRC sample SR6 continued to increase, the fibers gradually separated from the sample matrix and some of the steel and polypropylene fibers were straightened. pulled out or broken, and the bending load value of the sample gradually decreased. This process progressed more slowly until the deflection reached 45 mm and the samples could still withstand a certain residual load. This shows that the addition of hybrid fibers significantly improved the bending properties and post-forming ability of the recycled concrete[16], [26].

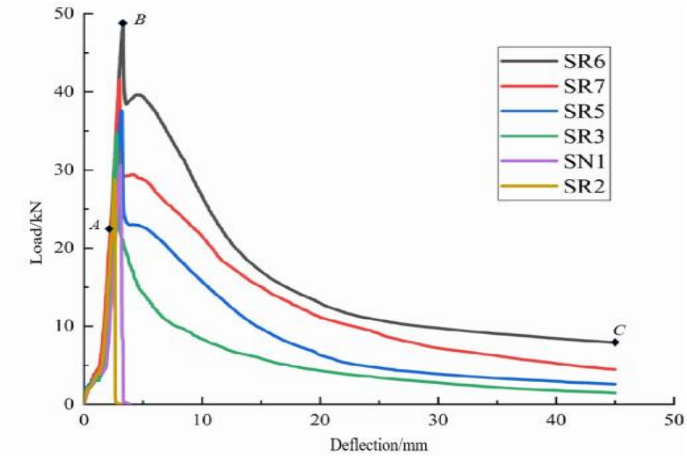

Figure 2: Load-deflection curves of recycled concrete specimens SN1, SR2, SR3, SR5~SR7

Effect of volume admixture of steel fibers on the flexural toughness of recycled concrete slabs

From Figure 3, it can be seen that the flexural ultimate load and the post-peak section of the load-deflection curve of HFRC specimens with different steel fiber admixtures have large differences. The amount of steel fiber admixture increased from 0.8% to 1.2%, i.e., the flexural ultimate load increased by 29.19% and 19.63% and the initial crack deflection increased by 20.15% and 29.82% for HFRC specimen SR6 relative to HFRC specimen SR5 and HFRC specimen SR7 relative to HFRC specimen SR3, respectively. The higher the amount of steel fibers, the flatter the post-peak section of the load-deflection curve of HFRC specimens, which showed better flexural toughness. This is because as the amount of steel fibers increases, the spacing between fibers decreases and the more steel fibers across the crack ends at the damage interface, the stronger their ability to transmit stress, which in turn slows the expansion of cracks. Therefore, the increase of steel fiber admixture has improved the flexural load capacity and flexural toughness of hybrid fiber recycled concrete slabs[5].

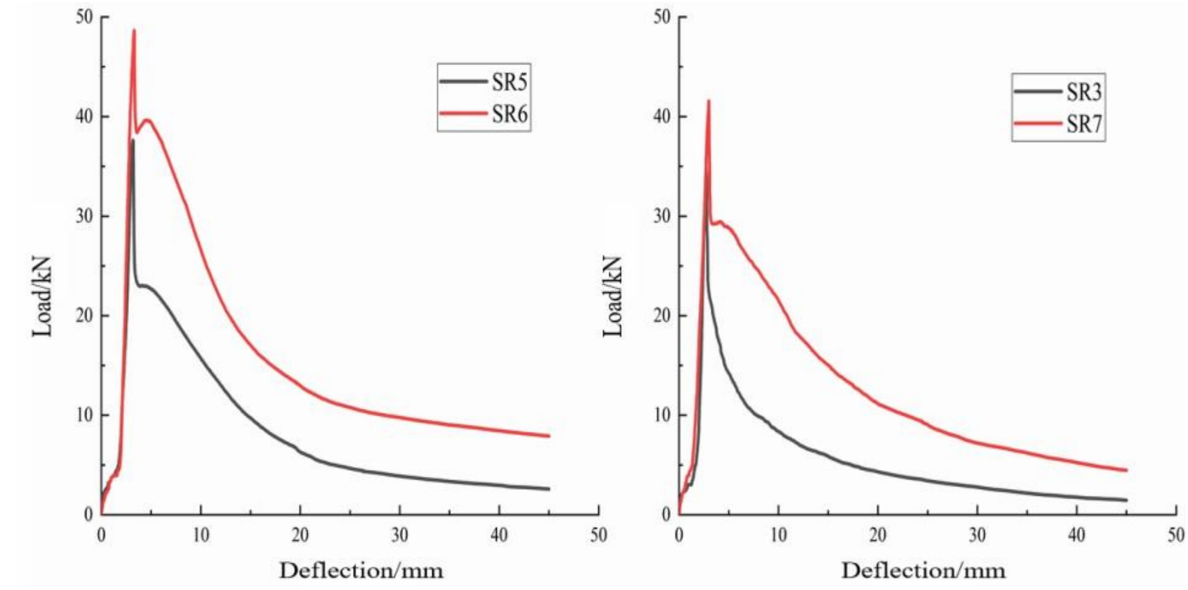

Figure 3: Comparison of load-deflection curves of HFRC specimens SR5 and SR6, SR3 and SR

Effect of steel fiber type on the flexural toughness of recycled concrete slabs

The flexural properties of HFRC with two different steel fibers also differ when the amount of steel fibers is certain. The ultimate flexural load of HFRC specimen SR5 increased by 8.45% compared with that of HFRC specimen SR3 when the steel fiber mixing rate was 0.8%, and the load-deflection curve was fuller and decreased more slowly in the post-peak section (see Fig. 4); When the steel fiber mixing rate was 1.2%, the flexural ultimate load of HFRC specimen SR6 was increased by 17.11% compared to HFRC specimen SR7.And as shown in Table 5, the crack width of HFRC specimen SR5 was reduced by 22.11% compared with that of HFRC specimen SR3. It can be seen that the ability of ultra-short microfilament steel fibers to strengthen, toughen and restrain plastic deformation of recycled concrete is significantly better than that of multi-anchored steel fibers[30].

A comparative analysis of steel fibers SF1 and SF2 shows that the main reasons for the difference in flexural performance of the two different fiber concrete slabs are: (1) In terms of tensile strength, ultra-short microfilament steel fibers SF1 are twice as strong as multi-anchored steel fibers SF2, which provide superior reinforcement to the recycled concrete matrix; (2) The diameter of steel fiber SF1 is less than half of SF2, so when the fiber volume mixing is the same, the number of fibers of SF1 is more than four times that of SF2, so the spacing between steel fibers is greatly reduced, and its bridging ability in the crack section of the matrix is greatly enhanced, so its toughening and cracking resistance is also enhanced; (3) Ultra-short microfilament steel fibers SF1 are ultra-short steel fibers, which have a more blunt sidewall effect compared to SF2 and better dispersion in the recycled concrete matrix, thus effectively limiting the formation and expansion of micro cracks parallel to the interface [31][32]–[35].

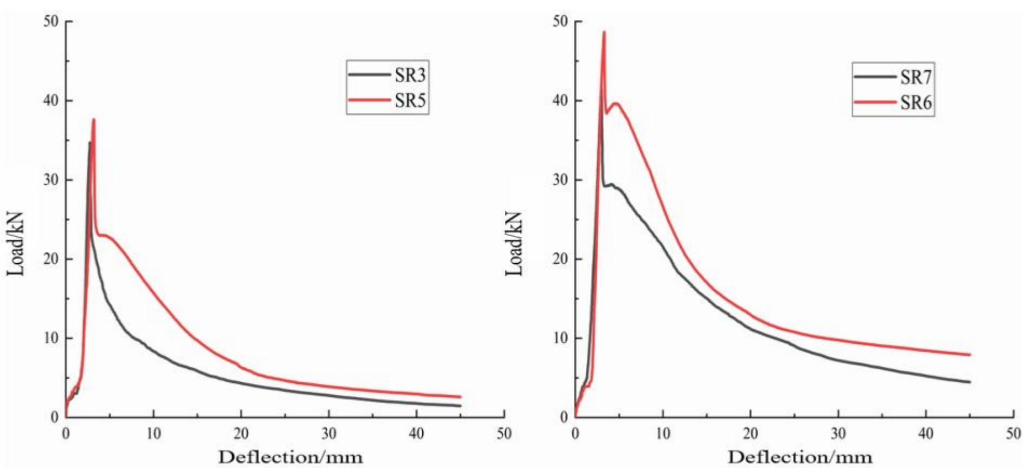

Figure 4: Comparison of load-deflection curves of HFRC specimens SR3 and SR5, SR7 and SR6

Effect of polypropylene fibers on the flexural toughness of recycled concrete slabs

The load-deflection curves of specimen SR4 and HFRC specimen SR6 with single mixed steel fiber SF1 are shown in Figure 5. As can be seen from Figure 5, compared with specimen SR4, the flexural ultimate load of HFRC specimen SR6 increased by 4.18%, the initial crack deflection increased by 9.52%, and the residual bearing capacity increased by 43.30%, and the post-peak section of its load-deflection curve was smoother and fuller, presenting a better post-crack flexural toughness. This is because of the small diameter of polypropylene fibers (PPF), the huge number of fibers mixed into the recycled concrete, and the huge number of PPF dispersed in various locations in the matrix, which can fill the voids in the specimen and improve its compactness; The elongation of PPF is large, and its elongation deformation does work in the process of resisting crack expansion, absorbing a large amount of energy, which can alleviate the crack expansion rate and the phenomenon of stress concentration at the tip[34], [35]; In addition, after the surface roughing process, the bond between PPF and matrix is stronger. When some of the steel fibers quit working, PPF can continue to play the role of bridge linkage to limit the formation and expansion of micro-cracks and improve the flexural toughness and crack resistance of recycled concrete [10], [21], [22]; In summary, it can be seen that the steel fibers with high elastic modulus can improve the flexural ultimate load capacity of recycled concrete, and the polypropylene fibers with low elastic modulus can improve the post-crack toughness and plastic crack resistance of recycled concrete, and the positive mixing effect after the superposition of the two can significantly improve the flexural performance of the matrix. Therefore, the flexural toughness of the HFRC specimen SR6 with a small amount of PPF was better than that of the specimen SR4 with a single mixing of SF1.

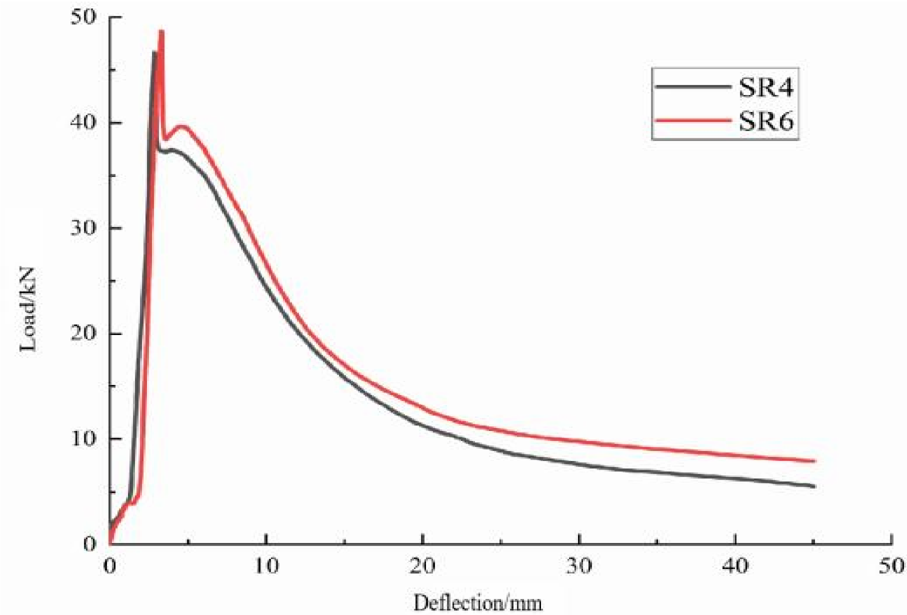

Figure 5: Comparison of load-deflection curves of HFRC specimens SR4 and SR6

Energy-deflection curve

Equation (1) is used to integrate the load-deflection curve for circular cylindrical structure[36][37] and the obtained energy absorption value is corrected by Equation (2), and Figure 6 shows the energy-deflection curve after the correction process.

$$\omega_o = \int_0^\delta F \mathrm{d}\delta \qquad 1$$

$$\omega = \omega_0 \left(\frac{t_0}{t}\right)^\beta \left(\frac{d_0}{d}\right) \qquad 2$$

Among them $\beta = 2.0 - (\delta - 0.5)/80$ w is the corrected absorbed energy, J; w_0 is the absorbed energy obtained by integration, J; F is the measured value of the load on the plate, kN; d is the measured value of deflection at the center of the plate, mm; t and d are the average thickness and average diameter of the plate, respectively, in mm; t_0 and d_0 are the nominal thickness and nominal diameter of the plate, respectively, mm.

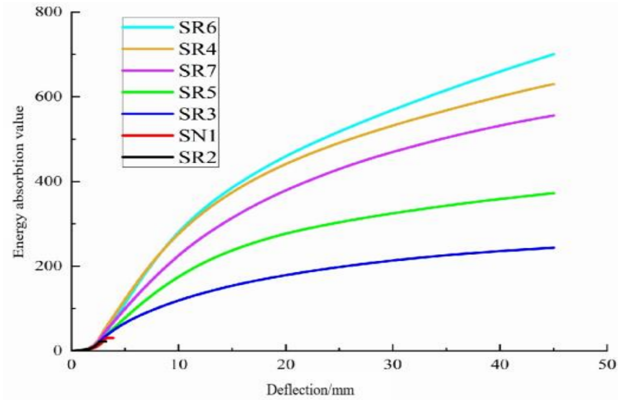

Figure 6: Energy-deflection curve

From Figure 6, it can be seen that the average value of energy absorption correction for the plain concrete specimen SN1 and the recycled concrete specimen SR2 without fiber mixing is only 31 J and 22 J, respectively, due to the brittle destabilization damage occurred at the early stage of loading; The energy absorption values of the specimens with single steel fibers SR4 or steel-polypropylene hybrid fibers HFRC increased to different degrees compared to the control specimen SR2. The corrected average values of energy absorption for each group of specimens at different deflections are shown in Table 6. The energy absorption values of the recycled concrete specimens SR3 to SR7 with different fiber types and amounts were 11.09 times, 28.64 times, 16.91 times, 31.82 times, and 25.27 times higher than those of the non-fiber control specimen SR2 when the test termination conditions were reached[38], [39].

Table 6: Average value of energy absorption correction for each specimen group

Specimen set	Average value of energy absorption correction at different deflections / J				
	5mm	10mm	20mm	40mm	45mm
SN1	31 3.87mm	—			
SR2	22 3.21mm	—			
SR3	66	119	179	236	244
SR4	122	277	441	601	630
SR5	78	175	277	358	372
SR6	113	280	460	660	700
SR7	99	225	379	532	556

In combination with Figure 6 and Table 6, comparing the two groups of HFRC specimens with different volume mixing of steel fibers, it can be seen that the average value of energy absorption correction of specimen SR7 increased by 50.0%, 89.1%, 111.7%, 125.4% and 127.9% when the central deflection was 5, 10, 20, 40 and 45 mm, respectively, compared with SR3. Therefore, the energy absorption level of HFRC increases with the increase of steel fiber mixing, and the energy absorption values of the two groups of HFRC specimens with different steel fiber mixing increase with the increase of deflection at the center point; Compared with HFRC specimen SR6 and HFRC specimen SR7, the energy absorption values of specimen SR6 increased by 24.4%, 21.4%, and 25.9% when the center deflection was 10, 20, and 45 mm, respectively, because the steel fiber SF1 had greater tensile strength compared with SF2, and its strengthening and crack stopping effect was better, and the end hooks of steel fiber SF2 were straightened and the toughening effect became worse at the later stage of test loading. 21.4% and 25.9%, respectively. Therefore, the energy absorption level of steel fiber SF1 is significantly stronger than that of SF2; Compared with the single steel fiber recycled concrete specimen SR4, the average value of energy absorption correction of HFRC specimen SR6 increased by 1.1%, 4.3% and 11.1% at the center deflection values up to 10, 20 and 45 mm, respectively, and the difference between the energy absorption values of the two increased with the increase of the center deflection. It can be seen that the energy absorption capacity of HFRC is stronger due to its fiber-positive mixing effect. The is consistent with studies done by Wu et al [14], [27], [40] , where the steel fibers were distributed in a three-dimensional manner within the matrix of concrete, which effectively improved the failure mode of the concrete and significantly improved strength of the Concrete.

Comparing the damage morphology, load-deflection curves and energy-deflection curves of specimens SR3 to SR7, it can be concluded that the optimal combination of fiber mixing for HFRC bending performance is mixing of 1.2% steel fiber SF1 with 0.11% polypropylene fiber PPF.

V. Conclusion

In this article, a modified electro-hydraulic servo tester was used to carry out the flexural toughness test of hybrid fiber recycled concrete circular plate method, carried out with reference to the Standard for Fiber Concrete Test Methods (CECS 13:2009), The following conclusions can be obtained from the study of the effects of fiber admixture, steel fiber type and polypropylene fiber on the mechanical properties of recycled concrete in terms of flexural toughness:

1. 50% recycled coarse aggregate replacement rate of recycled concrete flexural damage form is more similar to ordinary concrete, are brittle damage, the replacement of recycled coarse aggregate leads to more rapid damage after the initial cracking of concrete; The flexural damage patterns of HFRC are all ductile damage.
2. Incorporation of steel and polypropylene fibers with different fiber admixtures and mixing methods can improve the compressive and flexural properties of recycled concrete to varying degrees, with compressive strength increasing by 2.41% to 17.76% and flexural ultimate load increasing by 20.45% to 68.75% compared to the recycled concrete without fiber admixture.
3. When the amount of steel fiber mixing is certain, there is also a difference in the bending performance of HFRC with two different steel fibers. Compared with the multi-anchor steel fiber SF2, the flexural toughness of HFRC with ultra-short microfilament steel fiber SF1 was better. When the fiber dose was 0.8% and 1.2%, the flexural ultimate load increased by 8.45% and 17.11%, respectively, and the crack width shrank by nearly 22%, showing a better level of post-peak crack control.
4. HFRC has better energy absorption capacity than single steel fiber recycled concrete, and the energy absorption value increases by 11.1% when the central deflection is 45 mm.
5. The flexural toughness of HFRC is best when the admixture of ultra-short microfilament steel fiber SF1 is 1.2% and the admixture of polypropylene fiber PPF is 0.11%.

Declaration of c conflict of Interests

The authors declare that there is no conflict of interest with any person/institution in the prepared article. IPE, ZE, LCO and SAM created the study concept and design, carried out the experiments, analyzed and interpreted the data.

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