

Document Version

Final published version

Licence

Dutch Copyright Act (Article 25fa)

Citation (APA)

Liu, G., Koetsier, M., Tošić, N., Ekkelenkamp, W., Nedeljković, M., Luković, M., & de la Fuente, A. (2025). Effect of incorporating different quantities of recovered steel fibres on the mechanical properties of new steel fibre-reinforced concrete. In M. Briffaut, & J. M. Torrenti (Eds.), *Proceedings of the 2025 fib International Symposium - Concrete Structures: extend lifetime, limit impacts* (pp. 1497-1504). (fib Symposium). fib. The International Federation for Structural Concrete.

Important note

To cite this publication, please use the final published version (if applicable).
Please check the document version above.

Copyright

In case the licence states "Dutch Copyright Act (Article 25fa)", this publication was made available Green Open Access via the TU Delft Institutional Repository pursuant to Dutch Copyright Act (Article 25fa, the Taverne amendment). This provision does not affect copyright ownership.
Unless copyright is transferred by contract or statute, it remains with the copyright holder.

Sharing and reuse

Other than for strictly personal use, it is not permitted to download, forward or distribute the text or part of it, without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license such as Creative Commons.

Takedown policy

Please contact us and provide details if you believe this document breaches copyrights.
We will remove access to the work immediately and investigate your claim.

Effect of incorporating different quantities of recovered steel fibres on the mechanical properties of new steel fibre-reinforced concrete

Guanzhi Liu^{1*}, Maria Koetsier², Nikola Tošić³, Wim Ekkelenkamp⁴, Marija Nedeljković⁵, Mladena Luković⁶, Albert de la Fuente⁷

¹*Civil and Environmental Engineering Department, Universitat Politècnica de Catalunya (UPC), Barcelona, Spain, guanzhi.liu@upc.edu*

²*Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, the Netherlands, M.Koetsier-1@student.tudelft.nl*

³*Civil and Environmental Engineering Department, Universitat Politècnica de Catalunya (UPC), Barcelona, Spain, nikola.tosic@upc.edu*

⁴*Twee R Recycling Groep BV, Hengelo, the Netherlands, w.ekkelenkamp@tweerrecycling-groep.eu*

⁵*Rijkswaterstaat, Ministry of Infrastructure and Water Management, Utrecht, the Netherlands, marija.nedeljkovic@rws.nl*

⁶*Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, the Netherlands, m.lukovic@tudelft.nl*

⁷*Civil and Environmental Engineering Department, Universitat Politècnica de Catalunya (UPC), Barcelona, Spain, albert.de.la.fuente@upc.edu*

Abstract

This study aims to investigate the effect of incorporating different quantities of steel fibres recovered during concrete recycling on the mechanical properties of new steel fibre reinforced concrete (SFRC). Mixes contained 20 kg/m³ and 25 kg/m³ of steel fibres, with recovered steel fibres at replacement levels of 0%, 10%, 30%, and 100%. The recovered fibres were tested and categorized to determine the effect of recycling on fibre properties. The compressive strength, elastic modulus, stress–strain behaviour in compression, residual flexural strength of SFRC and inductive test were tested. The results demonstrate that incorporating a small proportion of recycled fibre alongside virgin fibre is a feasible approach, with a 10% recycled fibre replacement yielding superior performance compared to using 100% virgin fibre alone.

Keywords: SFRC, recovered fibre, replacement ratio, stress-strain behaviour, residual flexural strength, inductive test

1 Introduction

The incorporation of recycled materials into construction practices has garnered significant attention in recent years, driven by the imperative to foster sustainable and eco-friendly solutions [1,2]. Among these sustainable approaches, the use of recovered fibres (RF) in fibre-reinforced concrete (FRC) has emerged as a promising avenue for enhancing both the mechanical properties of concrete and contributing to environmental conservation [3]. Many researchers have found that the use of RF from other wastes, such as waste tires and waste plastics, has a significant effect on the mechanical properties of

FRC, especially the flexural and tensile properties [4–6]. However, there are less investigated the RF from FRC. Notably, Liu et al. [7] and Brecht et al. [8] found that replacing 100% of virgin fibres (VF) with RF reduces the residual flexural strength of concrete in different decreased, primarily due to the shorter average length of recycled fibres. Consequently, some researchers have statistically classified RF geometry [9,10]. Additionally, the different recovery methods in the process of recovering RF have different effects on the fibres [8]. Moreover, the mechanical properties of some FRCs can be improved if different proportions of RFs are added to them [11].

The recovery of steel fibres from recycled concrete typically involves mechanical crushing followed by magnetic separation. These methods effectively extract steel fibres, but the recovered fibres often exhibit variations in shape, length. This inconsistency can make their performance in new concrete less predictable compared to virgin fibres. Despite these challenges, recovered fibres offer potential cost savings and environmental benefits, particularly in large-scale demolition contexts. While VFs are more uniform and reliable, they are also more expensive due to their controlled manufacturing process.

Hence, this study aims to investigate the fibres produced during the steel fibre-reinforced concrete (SFRC) recycling process and explore the effect of the resulting RFs on the mechanical properties of new SFRC. The findings are expected to contribute to the development of fully recycled concrete systems, supporting more sustainable construction practices.

2 Experimental programme

2.1 Material and specimen preparation

The cement used in the study was CEM II/A-L 42.5N (Cementos Molins, Spain). The NA was crushed limestone from a quarry in Villarcara (Barcelona province, Spain) used in fractions 0/4, 4/12, and 12/20 mm. MasterPozzolith 7003 (Master Builder Solutions, Germany) was used as a plasticizer. The virgin steel fibre used Dewmark Fibre Hendix prime 75/52 and the recovered steel fibre was obtained by crushed SFRC, as Fig. 1(left) shows. The RFs were classified according to their shape into four categories: complete, other, bent at an angle of more than 90 degrees and less than 90 degrees, as Figure 1(right) shows. The percentages of fibres in each category were 17 %, 14 %, 26 % and 43 %, respectively.



Fig. 1 The recovered steel fibre (left); types: a. Complete; b. Others; c. Angle < 90 degrees; d. Angle > 90 degrees (right)

In order to compare the effect of using different replacement ratios RF on SFRC, the replacement ratios used 10%, 30% and 100%, with fibre contents of 20 and 25 kg/m³, respectively. The details of the mixture design are shown in Table 1.

Table 1 Mix design of the tested concretes

Concrete	Cement (kg/m ³)	Water (kg/m ³)	Plast. (kg/m ³)	Aggregate (kg/m ³)			Fibre (kg/m ³)	
				0/4 mm	4/12 mm	12/20 mm	VF	RF
20-0%	350	192.5	2.27	779	264	703	20	0
20-10%							18	2
20-30%							14	6
20-100%							0	20
25-0%			2.45				25	0
25-10%							22.5	2.5
25-30%							17.5	2.5
25-100%							0	25

For each concrete, three cylindrical specimens ($\text{Ø}150 \times 300 \text{ mm}^3$) and three prismatic specimens ($150 \times 150 \times 600 \text{ mm}^3$) were cast in steel moulds for each concrete mix. All batching was performed in a laboratory concrete pan mixer (Collomatic 65/2 K-3) with a capacity of 35 l. For mixing, the fine and coarse aggregates were put together first and mixed for 60 s after which the water was added with the plasticizer and mixed another 60 s, after which the fibre was added for another 60 s of mixing. After hardening, the concrete specimens were demoulded and cured under 100 % relative humidity at a temperature of $22 \text{ °C} \pm 2 \text{ °C}$ (i.e., standard curing conditions) until testing.

2.2 Test procedures

All specimens were tested after 28 days of curing, each type concrete was tested stress–strain behaviour in compression, residual flexural strength and inductive test, all test details were displayed in Fig. 2.

Each group of three cylindrical specimens was used to test the stress-strain under compression and each group of three prismatic specimens was used to test the residual flexural strength. For the stress-strain testing, a compression testing machine (IBERTEST MEH 3000, Madrid, Spain) was used. The residual flexural strength was tested according to EN 14651 [12]. And the Servohydraulic Test System (Instron 8505) was used. The Figure 2 (a) and (b) shows the test layout. To investigate the causes of variability in experimental results for specific types of fibres, the number of fibres intersecting the cracked surface was quantified. This was achieved by conducting a bending test to failure, after which the number of bridging fibres was manually counted. Subsequently, an inductive test was performed to evaluate the fibre distribution corresponding to different recycled steel fibre (RSF) ratios. For this purpose, cubic specimens were extracted from the broken prism samples. Each prism yielded two cubes, denoted as Cube A and Cube B, with dimensions of 150 mm per side, as illustrated in Figure 2(c). These cubes were marked along three orthogonal directions—X, Y, and Z—and each direction was tested three times to obtain average values. In addition, the Barcelona (BCN) test, a widely accepted method for assessing the post-cracking performance of FRC [13], was conducted on the same cube specimens to enhance the reliability and comparability of the results, as depicted in Figure 2(e).

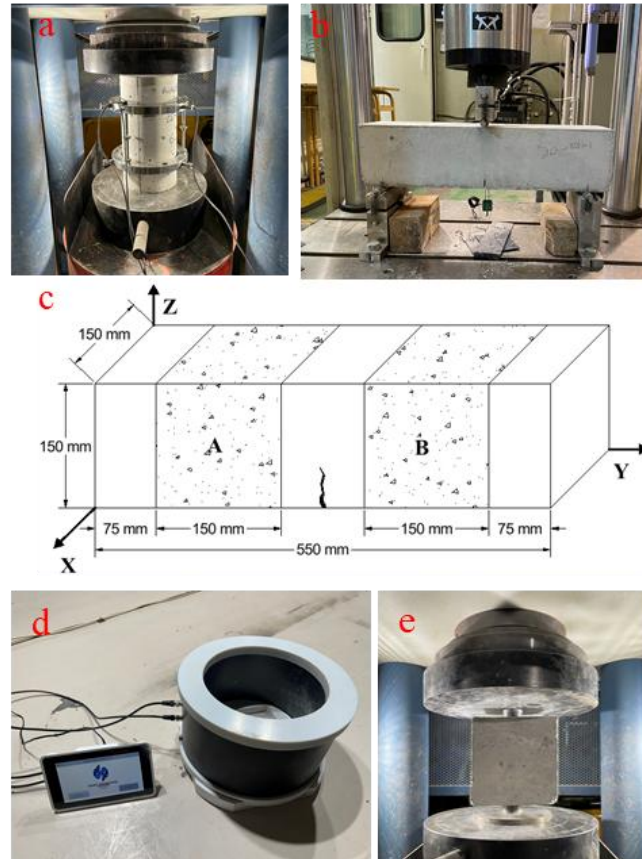


Fig. 2 The details of test layout: a. stress-strain under compression; b. 3-point bending test; c. Schematic diagram of cutting prismatic beams to obtain cubic specimens; d. Test set-up of inductive test; e. Barcelona test

3 Results and Discussion

3.1 Compressive stress-strain behaviour

Fig. 3 shows, for the different replacement percentages of RF, the stress-strain curves using a controlled load ratio for the fibre content of 20 and 25 kg/m³ respectively, where each curve is an average of all tested cylindrical specimens in each group. Regarding the shape of the ascending branch of the stress-strain curve, observing Figure 3, it can be seen that the shape of the stress-strain curves for all concretes is very similar, regardless of the RF replacement ratio. However, the stress-strain curve is different when the highest stress point is reached. At a fibre content of 20 kg/m³, the highest curve is 10% RF and the lowest curve is 30%. At a fibre content of 25 kg/m³, the highest curve is 100% and the lowest is 30%. This is because when the concrete reaches the highest point of stress, the concrete matrix and the fibres resist the stress together, while the shape and mechanical properties of RF are different from those of the VF, resulting in different curves.

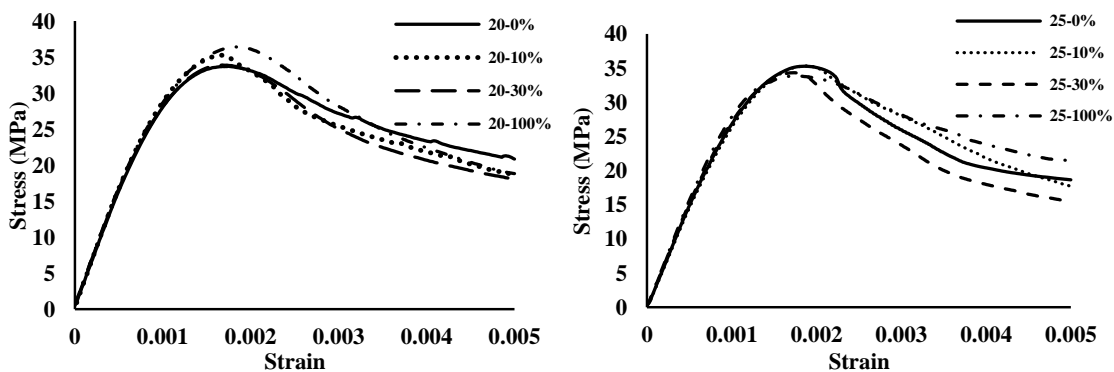


Fig. 3 Compressive stress-strain behaviour: 20 kg/m³ (left); 25 kg/m³ (right)

According to the stress-strain curve, the compressive strength of concrete can be obtained (usually considered to be the peak stress), as well as the modulus of elasticity [14]. Fig. 4 shows the compressive strength and elastic modulus (the coefficient of variation (CoV) in parentheses (in %)) for different RF substitution ratios in the fibre content of 20 and 25 kg/m³. For the fibre content of 20 kg/m³, the range of compressive strength is 34.0 to 36.4 MPa and the range of elastic modulus is 32.5 GPa to 33.5 GPa. While at a fibre content of 25 kg/m³, the compressive strength and modulus of elasticity were not affected by the RF replacement ratio. The result agrees with the previous study [11]. Therefore, RF doesn't affect the compressive strength and modulus of elasticity of concrete.

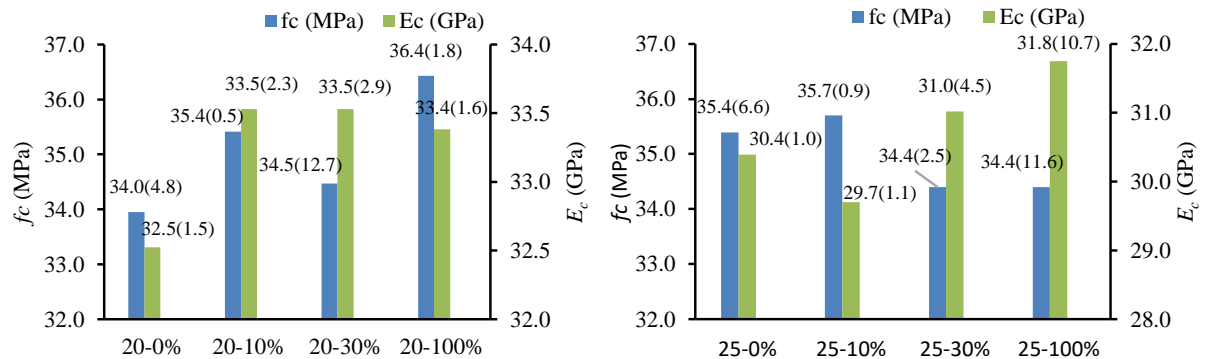


Fig. 4 compressive strength and elastic modulus: 20 kg/m³ (left); 25 kg/m³ (right)

3.2 Residual tensile strength

Fig. 5 shows the relationship between residual flexural strength after post-crack and crack mouth opening displacement ($f_{R,j-CMOD}$) with respect to RF replacement ratios (0%, 10%, 30% and 100%) at fibre contents of 20 and 25 kg/m³. For most cases, the plotted lines represent the average values obtained from three replicate test specimens. However, for the combinations 20-100%, 25-0%, and 25-30%, the data reflect the mean of only two specimens. In these specific cases, one of the three test results exhibited a significant deviation from the other two and was thus excluded from the average to ensure a more representative depiction of the material behaviour. The curves show no significant differences in terms of the flexural strength before the limit of proportionality (f_{LOP}). However, afterwards, there are appearing different situation. The curve of concrete using 10% RF is the highest than other concrete in both fibre contents. For the 20 kg/m³, the highest is 10% and then is 100% VF, the lowest is 100% RF. For the 25 kg/m³, there are different from the fibre content of 20 kg/m³. The concretes using mixture fibre are higher than using 100% VF at f_{R1} and f_{R2} . But the lowest is using 100% RF at f_{R3} and f_{R4} .

As shown in Table 2, a statistical analysis was conducted on the number of fibres observed on the fracture surfaces of all test specimens. The study found that at a fibre content of 20 kg/m³, the specimen with 100% RF replacement exhibited only 19 fibers on the fracture surface—significantly fewer than the other three groups. This reduction in fibre count may have compromised the crack-bridging capacity, thereby contributing to the lower residual flexural strength observed at full replacement. Interestingly, at a 10% replacement level, the number of fibres on the fracture surface didn't increase markedly compared to the other groups; however, this specimen demonstrated the highest residual flexural strength. This outcome aligns with findings from previous studies [11], suggesting that a small proportion of recycled fibres may improve post-cracking performance, potentially due to enhanced fibre dispersion or synergistic effects between recycled and virgin fibres. At a fibre content of 25 kg/m³, the fibre counts on the fracture surface, in descending order, correspond to the 10%, 30%, 0%, and 100% replacement groups. This distribution helps explain why the specimen with 10% recycled fibre replacement exhibited the highest residual flexural strength among the four, as a greater number of fibres contributes to improved crack-bridging and post-cracking load transfer capacity.

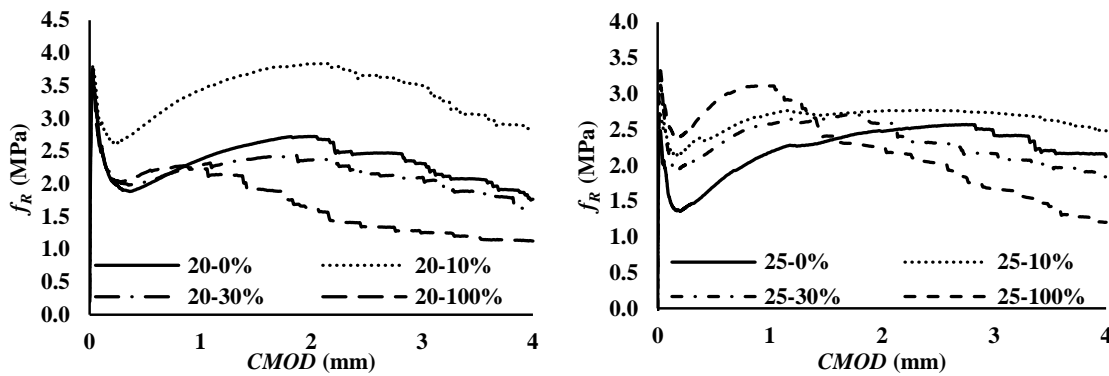


Fig. 5 Comparison of the effect of different replacement ratios on residual flexural strength of 20 kg/m³ (left) and 25 kg/m³ (right) of fibres.

Table 2 Statistics of the number of fibres on the fracture surface

Fibre number	0%	10%	30%	100%
20 kg/m ³	32	32	27	19
25 kg/m ³	43	52	47	31

To verify the reliability of the results, specimens were also tested using the BCN test. While BCN test does not replicate flexural stress conditions, it effectively reflects trends in SFRC performance, making it a useful tool for qualitative validation [13]. The test results for both fibre contents are presented in Fig. 6. At a fibre content of 20 kg/m³, the specimen with 100% RF shows a significantly sharper post-peak drop, forming the lowest curve. This behaviour is consistent with the trend observed in the three-point bending test, where 100% RF also resulted in reduced residual strength. In contrast, the responses of the 0%, 10%, and 30% RF specimens are more similar. A similar pattern is observed at a higher fibre content of 25 kg/m³, further supporting the consistency between the two testing methods and confirming the reliability of the experimental findings.

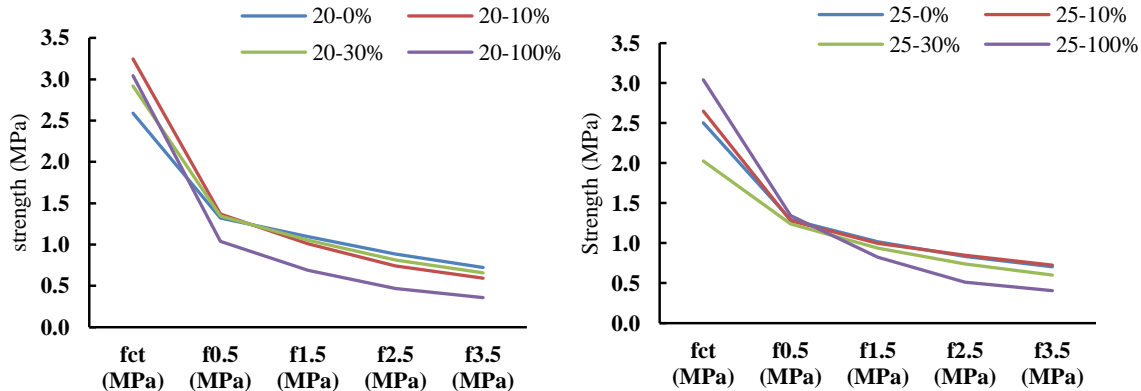


Fig. 6 The results of Barcelona test: 20 kg/m³ (left); 25 kg/m³ (right)

In Fig. 7, the f_{R1} and f_{R3} residual strengths and the CoV in parentheses (in %) of concrete with fiber content of 20 and 25 kg/m³ are presented. At a fibre content of 20 kg/m³, it is observed that the concrete with 10% RF exhibits the highest f_{R1} and f_{R3} values of 2.91 and 3.65 MPa, respectively, surpassing other concrete mixes. These values are 17.5% and 15.9% higher than those achieved with 100% VF. However, the concrete containing 30% and 100% RF shows lower strengths compared to 100% VF. At a fibre content of 25 kg/m³, the highest f_{R1} is achieved with 100% RF, reaching 2.87 MPa, which is 40.1% higher than the strength obtained with 100% VF. For f_{R3} , the highest value is recorded for 10% RF, reaching 2.77 MPa, representing a 7.9% increase compared to 100% VF. In summary, the results indicate that, at both fiber content levels, incorporating RF enhances certain properties of concrete, with the optimal percentage being 10% at 20 and 25 kg/m³. However, the concrete mixes with 30% and 100% RF exhibit lower strengths compared to those with 100% VF.

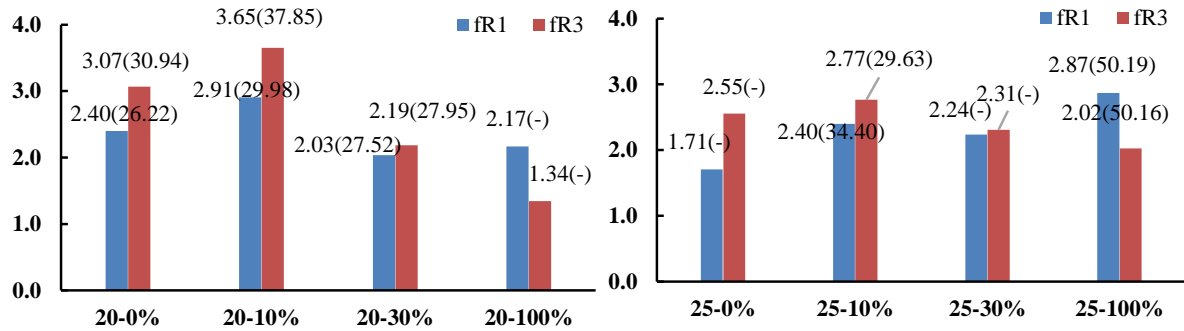


Fig. 7 The result of f_{R1} and f_{R3} : 20 kg/m³ (left) and 25 kg/m³ (right)

3.3 Inductive test

Fibre orientation has a significant impact on the mechanical properties of FRC. Accordingly, this study examined the three-dimensional fibre distribution under different RF replacement rates, with the results presented in Fig. 8. The ΔX , ΔY , and ΔZ represent the relative increases in inductance along three orthogonal directions in this figure. Given that steel fibres influence inductance when subjected to a magnetic field, these changes can be interpreted as indicative of the fiber distribution along each corresponding spatial axis. It can be found that the RF ratio not significantly affect the fibre orientation distribution for both fibre content compares the concrete with 0 % RF. In addition, the inductance values ΔX , ΔY , and ΔZ exhibit different rates of increase with rising fibre content. Notably, at 25 kg/m³, ΔZ shows a more significant increase compared to 20 kg/m³, accompanied by a noticeable change in the geometric representation of fibre distribution. Specifically, the originally equilateral triangle corresponding to the 20 kg/m³ mixture transforms into an acute triangle at 25 kg/m³, indicating a higher concentration of fibres aligned in the Z-direction. This enhanced fibre orientation in the Z-axis contributes to the improved residual flexural strength observed at the higher fibre content.

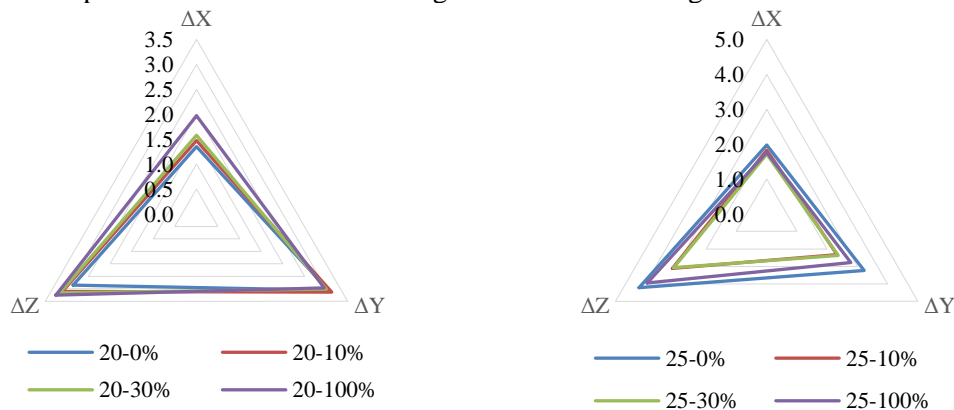


Fig. 8 The result of fibre orientation distribution: 20 kg/m³ (left) and 25 kg/m³ (right)

4 Conclusions

The main aim of this study was to investigate the impact of the replacement ratio of RF on the performance of SFRC. To achieve this goal, the stress–strain behaviour in compression of SFRC cylinders with varying RF replacement ratios was experimentally examined. Additionally, the residual flexural strength of SFRC with different RF replacement ratios was tested. Based on the findings of this study, the following conclusions can be drawn:

- The experimental results indicate that, within the studied range of RF substitution ratios, the compressive strength and modulus of elasticity of concrete remain relatively stable.
- Incorporating 10% RF yields the highest residual strengths at both 20 and 25 kg/m³ fibre contents, outperforming 100% VF by up to 17.5%. However, higher RF replacement rates result in strength reductions; for instance, at 20 kg/m³, the f_{R1} and f_{R3} values for 100% RF are approximately 33.3% and 30.2% lower, respectively, than those of the 10% RF mix.

- The test results indicate that within the range of RF substitution rates studied, the overall fibre orientation remains relatively unchanged; however, an increase in fibre content leads to a noticeable rise in fibre concentration along the Z-direction.

The results of this study are valid for the range of parameters and variables tested. However, future research should explore the durability of RSF within structural applications, as this could significantly impact the long-term performance of SFRC. It is anticipated that the findings from this study will contribute to the broader understanding of SFRC and its potential role in advancing the circular economy by promoting the reuse of materials in construction.

Acknowledgements

Authors thanks to the project HEAT (PID2023-149321OB-C32) and the funding from the China Scholarship Council (CSC) grant number 202106930007.

References

- [1] L. Chen, M. Yang, Z. Chen, Z. Xie, L. Huang, A.I. Osman, M. Farghali, M. Sandanayake, E. Liu, Y.H. Ahn, A.H. Al-Muhtaseb, D.W. Rooney, P.-S. Yap, Conversion of waste into sustainable construction materials: A review of recent developments and prospects, *Materials Today Sustainability* 27 (2024) 100930. <https://doi.org/10.1016/j.mtsust.2024.100930>.
- [2] T. Tazmeen, F.Q. Mir, Sustainability through materials: A review of green options in construction, *Results in Surfaces and Interfaces* 14 (2024) 100206. <https://doi.org/10.1016/j.rsurfi.2024.100206>.
- [3] K.M. Liew, A. Akbar, The recent progress of recycled steel fiber reinforced concrete, *Construction and Building Materials* 232 (2020) 117232. <https://doi.org/10.1016/j.conbuildmat.2019.117232>.
- [4] Cementitious Composites Reinforced with Recycled Fibres | SpringerLink, (n.d.). https://link.springer.com/chapter/10.1007/978-3-319-56797-6_8 (accessed January 21, 2025).
- [5] Fresh and hardened state properties of waste tire fiber and steel fiber reinforced concrete, *Materials Today: Proceedings* 80 (2023) 443–448. <https://doi.org/10.1016/j.matpr.2022.10.195>.
- [6] Z. Duan, Q. Deng, C. Liang, Z. Ma, H. Wu, Upcycling of recycled plastic fiber for sustainable cementitious composites: A critical review and new perspective, *Cement and Concrete Composites* 142 (2023) 105192. <https://doi.org/10.1016/j.cemconcomp.2023.105192>.
- [7] G. Liu, N. Tošić, A. De La Fuente, Recycling of Macro-Synthetic Fiber-Reinforced Concrete and Properties of New Concretes with Recycled Aggregate and Recovered Fibers, *Applied Sciences* 13 (2023) 2029. <https://doi.org/10.3390/app13042029>.
- [8] B. Vandevyvere, H. Pauwels, L. Vandewalle, The recycling potential of fibre reinforced concrete with 4D Dramix® fibres: Experimental analysis and model verification, *Construction and Building Materials* 444 (2024) 137781. <https://doi.org/10.1016/j.conbuildmat.2024.137781>.
- [9] G.-T. Xu, M.-J. Liu, Y. Xiang, B. Fu, Valorization of macro fibers recycled from decommissioned turbine blades as discrete reinforcement in concrete, *Journal of Cleaner Production* 379 (2022) 134550. <https://doi.org/10.1016/j.jclepro.2022.134550>.
- [10] J. Wang, Y. Li, Z. Qiu, Y. Zhang, Experimental research on compressive properties of recycling polypropylene (PP) fiber recycled coarse aggregate concrete, *Journal of Building Engineering* 76 (2023) 107403. <https://doi.org/10.1016/j.job.2023.107403>.
- [11] G. Liu, M. Hunger, N. To, Effect of free and embedded polypropylene fibres recovered from concrete recycling on the properties of new concrete, *Construction and Building Materials* (2023).
- [12] Test method for metallic fibered concrete - Measuring the flexural tensile strength (limit of proportionality (LOP), residual), (2005).
- [13] E. Galeote, A. Blanco, S.H.P. Cavalaro, A. De La Fuente, Correlation between the Barcelona test and the bending test in fibre reinforced concrete, *Construction and Building Materials* 152 (2017) 529–538. <https://doi.org/10.1016/j.conbuildmat.2017.07.028>.
- [14] G.-F. Belén, M.-A. Fernando, C.L. Diego, S.-P. Sindy, Stress–strain relationship in axial compression for concrete using recycled saturated coarse aggregate, *Construction and Building Materials* 25 (2011) 2335–2342. <https://doi.org/10.1016/j.conbuildmat.2010.11.031>.