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Effects of Stainless-Steel Waste Metal Strips and Recycled Aggregate on the Structural Behavior of Reinforced Concrete Beam: Experimental Case Study

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Abstract

This study investigates the structural performance of reinforced concrete (RC) beams incorporating recycled aggregates (RA) and stainless-steel fibers (SSF) derived from commercial metal waste. A total of nine RC beams (1.5 m × 0.15 m × 0.1 m) were cast using varying RA contents (0%, 25%, and 50%) sourced from hollow blocks, along with SSF dosages of 0%, 0.25%, and 0.5% by volume. Additionally, 27 cubes and 9 cylinders were prepared to evaluate compressive and tensile strengths for each mix design. The beams were tested under two-point loading using a 1500 kN frame. Experimental results demonstrated that the inclusion of SSF significantly enhanced the flexural behavior and tensile strength of the concrete matrix, while the use of RA led to a general reduction in mechanical behavior. However, the strength loss due to RA was partially offset by the presence of SSF. Compressive and tensile strength increased consistently with higher SSF content across all RA levels, with the most notable gains observed at 0.5% SSF. The increased density of the specimens was attributed to the high specific gravity of SSF (8000 kg/m³) compared to conventional concrete (2400 kg/m³). Overall, the incorporation of SSF improved the mechanical performance of RC beams and mitigated the adverse effects associated with recycled aggregates. All tests and evaluations were conducted by BS 8110-1:1997.

Keywords: Concrete; Beam; Flexural; Recycled Aggregate; Stainless-steel; Waste Metal Strips

1. Introduction

Concrete is the most widely used construction material globally, recognized for its versatility, strength, and durability. However, its brittle nature and limited tensile strength pose structural challenges, particularly in load-bearing applications (Dahake & Charkha, 2016; Tadepalli et al., 2009). These limitations, combined with growing environmental concerns over natural resource depletion, high carbon emissions, and construction waste generation, have prompted the development of more sustainable alternatives. Green concrete has emerged as a promising solution, incorporating recycled and industrial waste materials into traditional concrete mixtures. Among these, the partial or full replacement of natural coarse aggregates with recycled aggregates (RA), such as crushed hollow blocks from demolished structures, helps conserve raw materials, reduce landfill waste, and lower transportation-related emissions. Additionally, the integration of stainless-steel fibers (SSF) derived from industrial waste, such as lathe machining scraps, improves mechanical properties, including tensile, flexural, and compressive strength (Ahmad et al., 2023; Çelik et al., 2022; Khoso et al., 2022; Neeraja et al., 2017; Sathe et al., 2024). When handled and distributed properly within the mix, these fibers also mitigate the accumulation of non-biodegradable waste, contributing further to environmental sustainability (Prasad et al., 2020; Çelik et al., 2022).

Numerous studies have explored the effects of incorporating recycled aggregates in concrete. Yang et al. (2020) found that replacing natural aggregates with 30%-100% RA in reinforced concrete beams slightly reduced compressive strength but maintained acceptable structural behavior. Similarly, Sagheer et al. (2023) reported increased water absorption and decreased compressive strength in beams with 50% and 100% RA, while shear strength remained largely unaffected. Visintin et al. (2022) found that the life-cycle assessment revealed minimal differences in global warming potential across different generations of concrete production, while notably highlighting substantial reductions in the use of virgin materials. Zakrzewski and Domski (2023) noted improved deflection behavior in beams made with RA and waste steel fibers, demonstrating that recycled materials can perform comparably to natural alternatives in certain contexts.

Parallel research on steel fiber reinforcement, particularly from waste sources, has shown significant improvements in mechanical performance. Studies have highlighted the ability of steel fibers to bridge cracks, increase ductility, and improve post-cracking behavior (Dahake & Charkha, 2016; Tadepalli et al., 2009). Gencel et al. (2011) and Sharma and Ahuja (2015) noted that although workability decreases with fiber content, fiber-reinforced concrete (SFRC) exhibits boosted tensile and impact resistance, making it suitable for slabs, pavements, and industrial floors. Behbahani et al. (2011) reported that adding 1% steel fiber to concrete grades C30 and C50 optimized both compressive and flexural strength.

More recent studies have investigated the combined use of RA and steel fibers in structural elements. Kachouh et al. (2021) tested deep beams with 100% RA and up to 3% steel fibers, finding significant improvements in shear strength and post-cracking capacity, especially at 2%-3% fiber content. Anike et al. (2022) confirmed the positive impact of combining RA and steel fibers on flexural behavior. Elsayed et al. (2023) used aluminum waste fibers in beams with RA and observed enhanced shear resistance, although excessive fiber content reduced deflection capacity. Innovative approaches have also been explored: Eri et al. (2019) studied bamboo reinforcement with RA and noted improved crack control, while Falih et al. (2020) demonstrated that PET strips used in place of steel bars increased failure loads by up to 25%. Sancak and Ozyurt. (2022) found that incorporating 10%-20% industrial iron chips improved ductility with minor strength reduction, whereas 40% maximized strength but increased brittleness. Kanagaraj et al. (2024) and others further reinforced the value of integrating fiber and recycled components for sustainable concrete development.

Despite promising results, variability in fiber content, distribution, and interaction with recycled aggregates presents ongoing challenges. Further research is needed to optimize mix designs that balance mechanical performance, durability, and workability. This study addresses this gap by experimentally evaluating the combined effect of stainless-steel fibers and recycled aggregate content on the flexural behavior and strength characteristics of reinforced concrete beams, contributing to the broader goal of sustainable construction practices.

2. Study Program

In this investigation, natural sand was utilized as the fine aggregate (see Figure 1) while maintaining a consistent cement content across all mix variations. Two distinct types of coarse aggregates were incorporated: natural gravel (Figure 2) and crushed hollow block aggregate (Figure 3). The selection of raw materials complied with the relevant British Standards [B. EN, BS 882:1992, BS EN, 1097-3:1998, and BS EN, 197-1:2000], as illustrated in Figures 4-6. Waste stainless steel strips (S316) sourced from Intaj Suhar were introduced into the experimental concrete mixes at 0.25% and 0.50% by volume. These strips were cut to dimensions ranging from 3 to 5 cm in length and 0.15 mm in thickness (see Figure 7). The mechanical properties of the S316 stainless steel waste strips are presented in Table 1, while their chemical composition is detailed in Table 2. Additionally, crushed aggregate (recycled aggregate) replaced the natural gravel at 25% and 50% by weight. The replacement levels of 0%, 25%, and 50% recycled aggregates (RA) were selected to represent a progressive substitution approach, aligning with ranges commonly investigated in the literature to evaluate structural performance while maintaining acceptable strength and durability. The water-to-cement ratio for all mixes was set at 0.5, with a mixed design ratio of 1:2:4/0.5, a standard formulation commonly used in construction. The water-cement ratio of 0.5 was chosen based on its common use in structural concrete applications, offering a practical balance between workability and strength. The specific details of the experimental concrete mixes are provided in Table 3. The slump of all trial mixes was maintained within the range of 80 to 100 mm.

The use of SSF and RA in concrete presents significant sustainability benefits aligned with circular economy principles. Incorporating SSF derived from industrial metal waste not only diverts non-biodegradable materials from landfills but also reduces the demand for virgin steel fibers, contributing to resource conservation and reduced energy consumption associated with fiber manufacturing. Similarly, replacing natural coarse aggregates with RA, sourced from construction and demolition waste, helps mitigate environmental degradation caused by quarrying activities and significantly lowers the volume of waste directed to landfills. This dual strategy not only reduces the carbon footprint of concrete production but also promotes more sustainable material cycles within the construction industry. As such, the integration of SSF and RA supports the development of greener, more resource-efficient infrastructure without compromising structural performance.

For each mix, three standard cubes (150 mm × 150 mm × 150 mm) and one standard cylinder (150 mm diameter × 300 mm height) were cast and tested to examine the effects of substituting natural aggregates with RA and introducing SSF on the compressive and tensile strength of the concrete. Before mixing, the aggregates underwent thorough characterization, including sieve analysis, moisture content determination, specific gravity, and absorption tests. The water content for fine, coarse, and recycled aggregate was 0.24%, 0.16%, and 0.1%, respectively. The specific gravity was 2.63, 2.74, and 2.53, respectively. The water absorption was 1%, 3%, and 5%, respectively.

To assess the flexural behavior of reinforced concrete beams, nine reinforced concrete beams, each with dimensions of 100 mm width × 150 mm depth × 1500 mm length, were cast and tested. Each beam contained two Ø8 steel bars in the tension zone and two Ø6 steel bars in the compression zone. To prevent shear failure and ensure flexural failure, Ø6 links were placed at 100 mm intervals as shear reinforcement, as shown in Figure 8. The experimental study of flexural behavior was carried out using an electronic dial gauge to measure the vertical displacement at the mid-span of the beams. A manual compression machine applied the load, and the applied force was recorded using a 600 kN load cell connected to a computer. The load was applied 0.45 m from the supports, which were positioned as simply supported. The test setup is shown in Figure 9.

Figure 1. Sand

Figure 2. Gravel

Figure 3. Recycled Aggregate

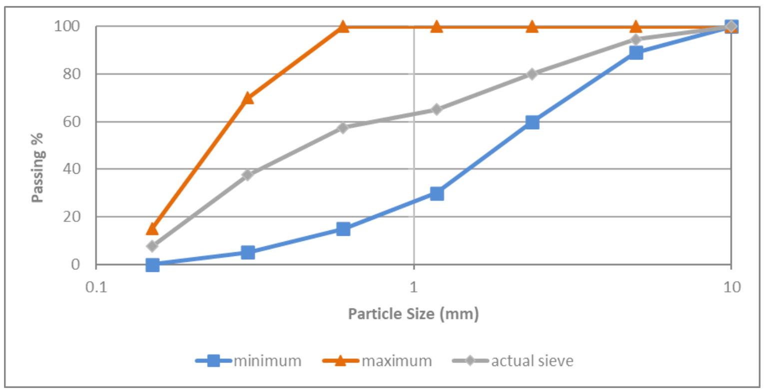


Figure 4. Grading of Sand

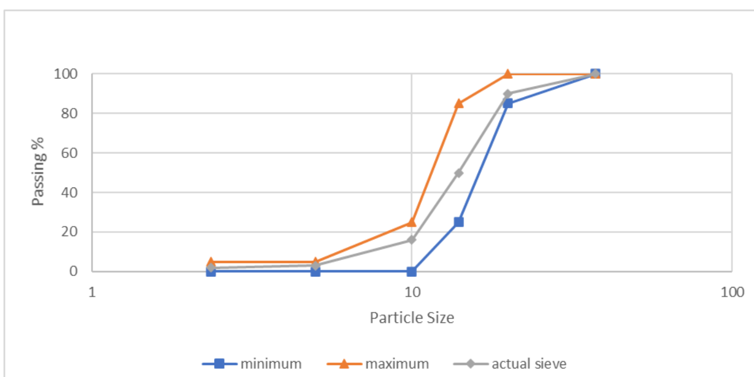


Figure 5. Grading of Gravel

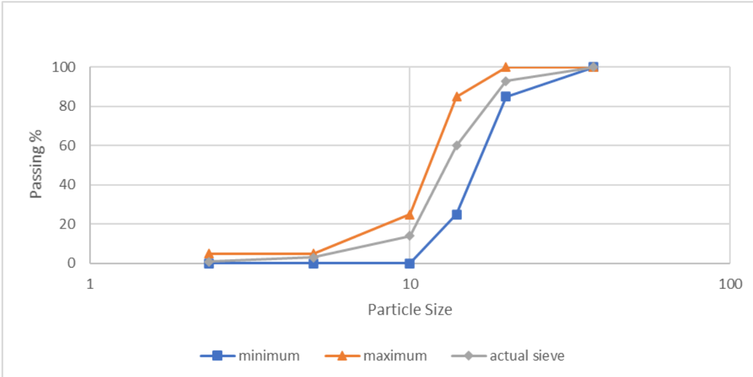


Figure 6. Grading of RA

Figure 7. SSF

Table 1. Mechanical Properties of S316

Material	Stainless Steel fiber
Shape	Spiral
Length (mm)	30 – 50
Width (mm)	1.0
Thickness (mm)	0.15
Cross-section	Rectangular
Density (kg/m^3)	7,500 – 8,000
Modulus of elasticity (N/mm^2)	190,000-200,000
Yield Stress (N/mm^2)	250 – 300
Ultimate Tensile Strength (N/mm^2)	550-650

Table 2. Chemical Components of S316 [Ibrahim et.al., 2023]

Component	Weight %
C	Max 0.08
P	0.045
Si	0.75
Mg	Max 2
Ni	10-14
N	0.10
Ag	0.03

Table 3. Concrete Trail Mix Proportion

Trail mix No.	Beam designation	Trial Mixes	Cement (kg)	Sand (kg)	Gravel (kg)	Water (litter)	RA %	RA (kg)	SSF%	SSF (kg)
TM1	B1	0%RA+0% SSF	17	34	68	8.5	0%	0	0%	0.0
TM2	B2	0%RA+0.25% SSF	17	34	68	8.5	0%	0	0.25%	0.7
TM3	B3	0%RA+0.5% SSF	17	34	68	8.5	0%	0	0.50%	1.5
TM5	B5	25%RA+0% SSF	17	34	51	8.5	25%	17	0%	0.0
TM6	B6	25%RA+0.25% SSF	17	34	51	8.5	25%	17	0.25%	0.7
TM7	B7	25%RA+0.5% SSF	17	34	51	8.5	25%	17	0.50%	1.5
TM9	B9	50%RA+0% SSF	17	34	34	8.5	50%	34	0%	0.0
TM10	B10	50%RA+0.25% SSF	17	34	34	8.5	50%	34	0.25%	0.7
TM11	B11	50%RA+0.5% SSF	17	34	34	8.5	50%	34	0.50%	1.5

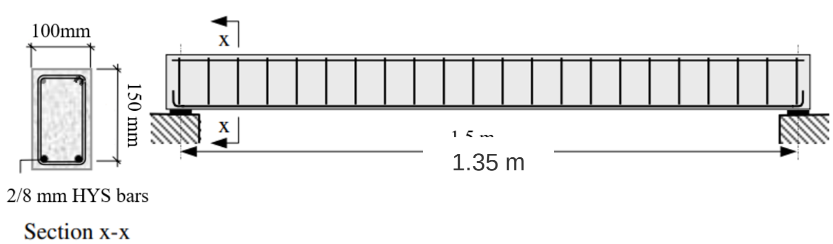


Figure 8. Design of the Adopted Simply Supported Beam.

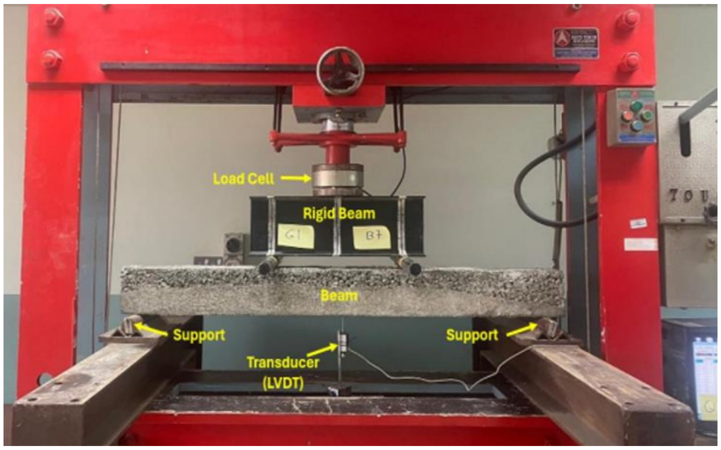
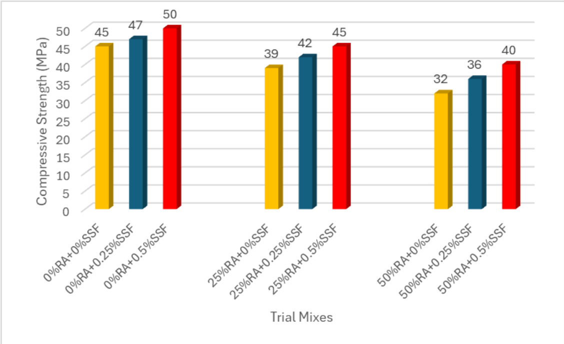


Figure 9. Test Setup

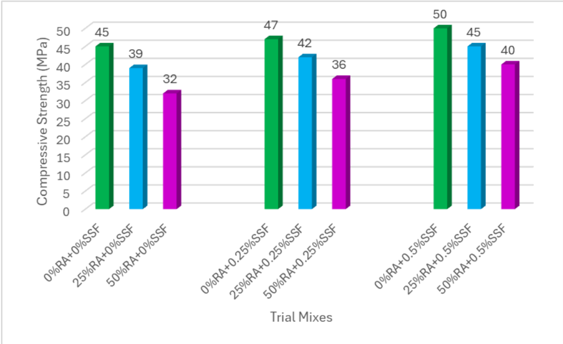
3. Results and Discussion

3.1. Compressive Strength of Concrete

For each trial mix, three concrete cubes were cast and tested. The average compressive strength was calculated, with the standard deviation approximately 3%. Figure 10 illustrates the impact of varying recycled aggregate (RA) and stainless-steel fiber (SSF) contents on the compressive strength of concrete. The mixes had been grouped by RA content, 0%, 25%, and 50%, and further subdivided by SSF stages of 0%, 0.25%, and 0.5%. The effects exhibit a clean trend: the inclusion of SSF consistently increased compressive strength across all RA%. At 0%RA, compressive strength extended from 45 MPa (0% SSF) to 47 MPa (0.25% SSF) and 50 MPa (0.5% SSF), reflecting gains of 4.4% and 11.1%, respectively. At 25% RA, strength increased from 39 MPa to 42 MPa and 45 MPa, corresponding to increases of 7.7% and 15.4%. The effect turned into even more pronounced at 50% RA, with compressive strength rising from 32 MPa (0% SSF) to 36 MPa (0.25% SSF) and 40 MPa (0.5% SSF), representing gains of 12.5% and 25%, respectively. These findings suggest that the relative development furnished with the aid of SSF increases with higher RA content, suggesting that SSF can compensate for the strength discount associated with recycled aggregates. Conversely, the effect of RA on compressive strength at fixed SSF stages was also evident. At 0% SSF, strength declined from 45 MPa at 0% RA to 39 MPa and 32 MPa at 25% and 50% RA, representing reductions of 13.3% and 28.9%. Similar reducing trends had been determined at 0.25% and 0.5% SSF, although the discounts were less excessive. For example, at 0.5% SSF, the strength reduced from 50 MPa to 45 MPa and 40 MPa as RA% increased from 0% to 25% and 50%, respectively. Overall, the results verify that even as recycled aggregates negatively affect compressive strength because of their inferior mechanical properties, the addition of SSF notably complements performance and mitigates those outcomes. Therefore, the blended use of RA and SSF can offer a possible technique for producing greater sustainable concrete with applicable structural overall performance, especially when higher SSF contents are employed



(a) Effect of SSF

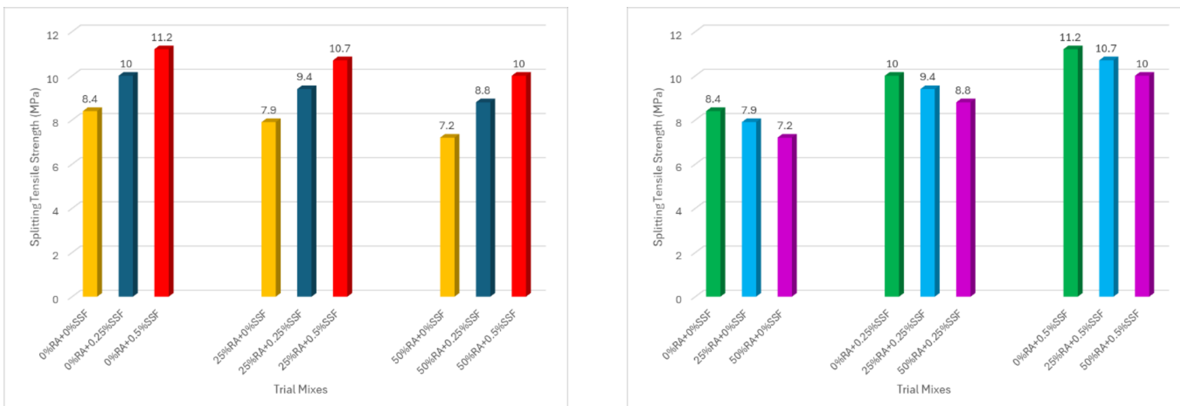


(b) Effect of RA

Figure 10. Concrete Compressive Strength of Cube after 28 days of Curing.

3.2. Splitting Tensile Test

The splitting tensile strength outcomes for diverse concrete mixes incorporating distinctive proportions of RA% and SSF% are provided in Figure 11. As located, the inclusion of SSF appreciably increases tensile strength throughout all RA levels. At 0% RA, the tensile strength extended from 8.4 MPa (0% SSF) to 10 MPa (0.25% SSF) and 11.2 MPa (0.5% SSF), corresponding to gains of 19.05% and 33.33%, respectively. At 25% RA, tensile strength rose from 7.9 MPa to 9.4 MPa and 10.7 MPa with 0.25% and 0.5% SSF, representing increases of 18.99% and 35.44%. Similarly, at 50% RA, the values increased from 7.2 MPa to 8.8 MPa and 10 MPa, reflecting improvements of 22.22% and 38.88%. These effects truly reveal that the fine impact of SSF on tensile strength becomes more significant because the RA content will increase, indicating that SSF correctly moderates the mechanical degradation related to recycled aggregates. On the other hand, the impact of RA% at constant SSF% shows a decreasing trend in tensile strength. At 0% SSF, strength declined from 8.4 MPa at 0% RA to 7.9 MPa and 7.2 MPa at 25% and 50% RA, respectively, equating to 5.95% and 14.29% reductions. Similar but less extreme reductions were noted at 0.25% and 0.5% SSF. Overall, recycled aggregates lessen splitting tensile strength due to their decreased mechanical properties; the addition of SSF, particularly at higher percentages, notably complements performance and compensates for strength loss. Therefore, for packages where recycled aggregates are used, incorporating higher contents of SSF presents a powerful strategy to maintain or even improve the tensile strength of concrete.

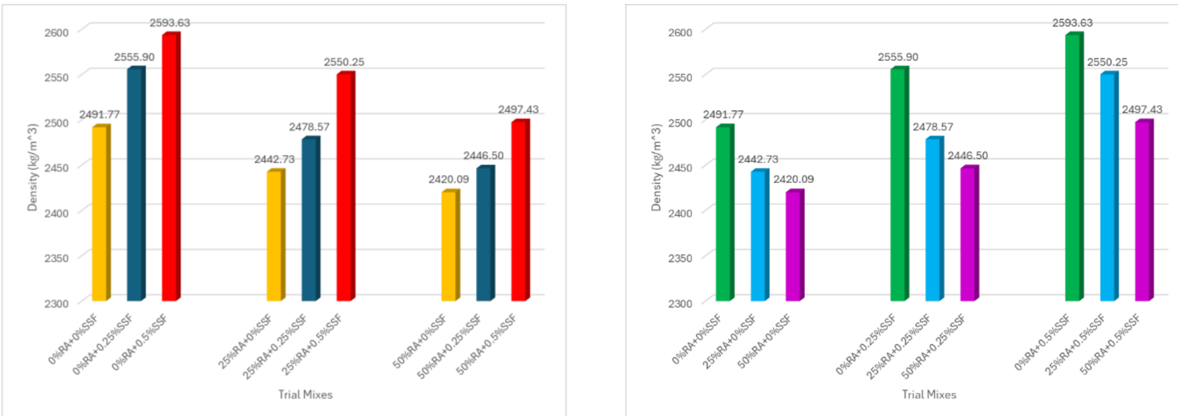


(a) Effect of SSF (b) Effect of RA

Figure 11. Concrete Splitting Tensile Strength of Cylinder after 28 days of Curing.

3.3. Concrete Density

The density consequences of the concrete trial mixes incorporating various proportions of RA% and SSF% are provided in Figure 12. The records indicate that increasing the SSF content always leads to better concrete density across all RA%. For instance, at 0% RA, the density expanded from 2491.77 kg/m³ (0% SSF) to 2555.90 kg/m³ (0.25% SSF) and similarly, to 2593.63 kg/m³ (0.5% SSF). A comparable trend changed into observed at 25% RA, in which the density rose from 2442.73 kg/m³ to 2478.57 kg/m³ and 2550.25 kg/m³, and at 50% RA, in which the values elevated from 2420.09 kg/m³ to 2446.50 kg/m³ and 2497.43 kg/m³, respectively. This increase in density is attributed to the high precise gravity of SSF (~8000 kg/m³), which drastically exceeds that of standard concrete (~2400 kg/m³), resulting in a denser composite matrix as fiber content material increases. Conversely, RA use caused a sizeable discount in concrete density at every SSF%. For instance, at 0% SSF, the density reduced from 2491.77 kg/m³ (0% RA) to 2442.73 kg/m³ (25% RA) and 2420.09 kg/m³ (50% RA). This decline is attributed to the porous and light-weight nature of recycled aggregates, which usually possess decreased specific gravity as compared to natural aggregates. However, the discount in density due to RA turned into partially mitigated through the inclusion of SSF, at better fiber contents. Overall, while RA tends to lessen the density of concrete, the addition of SSF complements it significantly, making the mixture a possible technique for balancing sustainability and structural integrity in concrete layout.



(a) Effect of SSF (b) Effect of RA

Figure 12. Concrete Density

3.4. Flexural Behavior of Reinforced Concrete Beams

Figures 13 through 18 comprehensively illustrate the load-displacement behavior of reinforced concrete beams incorporating varying percentages of SSF and RA, highlighting their combined effects on stiffness, strength, and ductility. At 0%RA (Figure 13), beams with increasing SSF (0%, 0.25%, and 0.5%) show a nonlinear load-displacement response characterized by an initial steep rise followed by a gradual slope, reflecting the transition from elastic to plastic behavior. The addition of SSF significantly improves load capacity and ductility, with peak loads rising from approximately 30.67 kN for the fiberless beam to 31.51 kN for the highest fiber content beam, alongside increased displacement capacity. This improvement is attributed to the crack-bridging action of stainless-steel fibers, which delays crack propagation and improves stress distribution, thereby enhancing post-cracking toughness and energy absorption.

When 25% RA is introduced (Figure 14), the beams show more pronounced differences: fiber-reinforced beams outperform the unreinforced counterpart in strength and ductility, although overall stiffness is reduced compared to 0% RA beams. Specifically, the beam with 0.5% SSF achieves the highest peak load (~29.99 kN), while the fiberless beam exhibits the greatest ductility but lowest stiffness. This pattern stems from the weakened aggregate–matrix interface and increased porosity caused by RA, which reduces mechanical behavior. However, the presence of fibers compensates for these weaknesses through greater crack control and confinement effects. The beam with 0.25% SSF strikes an optimal balance, providing improved stiffness without compromising ductility due to adequate fiber dispersion and absence of clustering.

At 50% RA content (Figure 15), the importance of SSF is further emphasized. Although the fiberless beam exhibits the highest initial stiffness due to the coarse aggregate's resistance to deformation, it fails at lower loads and displacements, indicating brittle behavior. Conversely, beams with 0.25% and 0.5% SSF demonstrate improved post-cracking presentation, with the 0.5% fiber beam reaching a peak load of about 29.12 kN and the greatest displacement (9.58 mm). This confirms that higher fiber dosage effectively counteracts the detrimental effects of high RA content by enhancing toughness and energy absorption despite the reduced initial stiffness, through mechanisms of crack bridging and load redistribution.

Figures 16 to 18 extend these findings by comparing beams across RA levels and SSF% in detail. Without fibers (Figure 16), increasing RA content reduces stiffness and peak load capacity, while slightly improving ductility due to increased flexibility and microcracking in the matrix. With 0.25% SSF (Figure 17), fibers mitigate strength losses and improve ductility at all RA levels, though stiffness still declines with more RA. At 0.5% SSF (Figure 18), the beams maintain high load capacities and show significant ductility improvements even at elevated RA percentages, highlighting the critical role of higher fiber content in strengthening and toughening recycled aggregate concrete. The consistent presence of SSF improves crack resistance, delays failure, and allows better energy dissipation, compensating for the porosity and weaker interfacial bonding introduced by RA.

In summary, increasing RA content tends to reduce stiffness and peak strength while enhancing ductility, reflecting the trade-offs inherent in using recycled materials. Meanwhile, incorporating SSF, particularly at higher percentages, significantly enhances load-carrying capacity, toughness, and ductility, effectively mitigating RA-related weaknesses and producing more durable, resilient, and structurally efficient concrete beams under flexural loading.

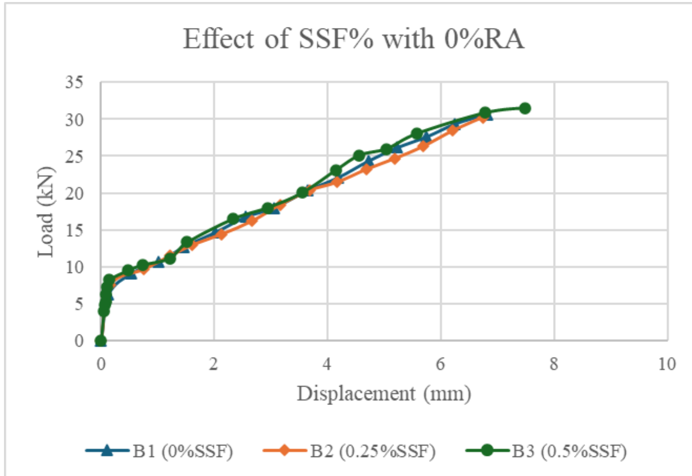


Figure 13. Effect of SSF% With 0%RA

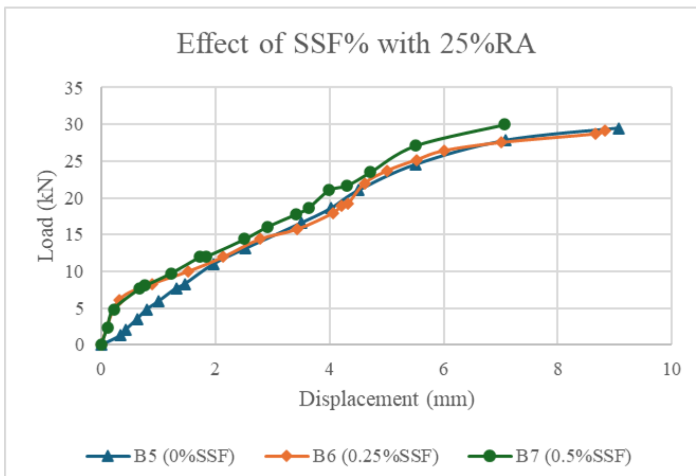


Figure 14. Effect of SSF% with 25%RA

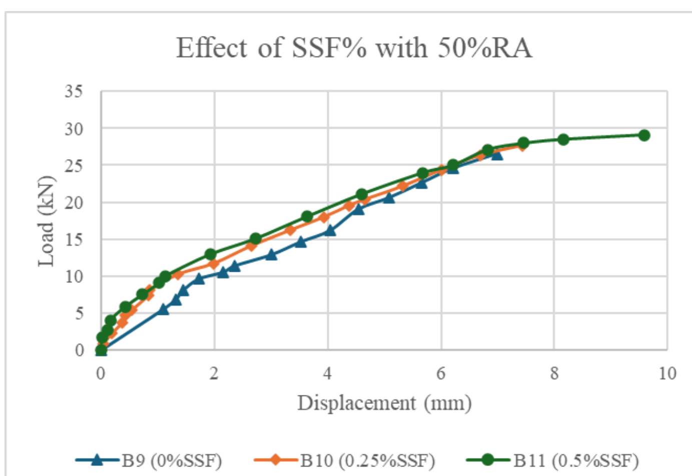


Figure 15. Effect of SSF% with 50% RA

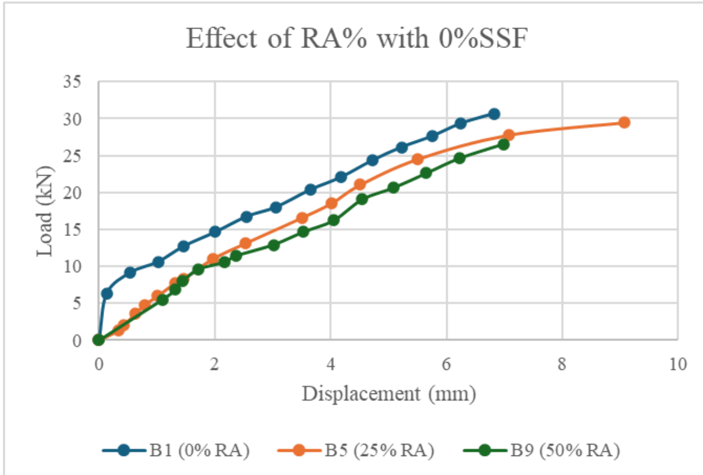


Figure 16. Effect of RA% with 0% SSF

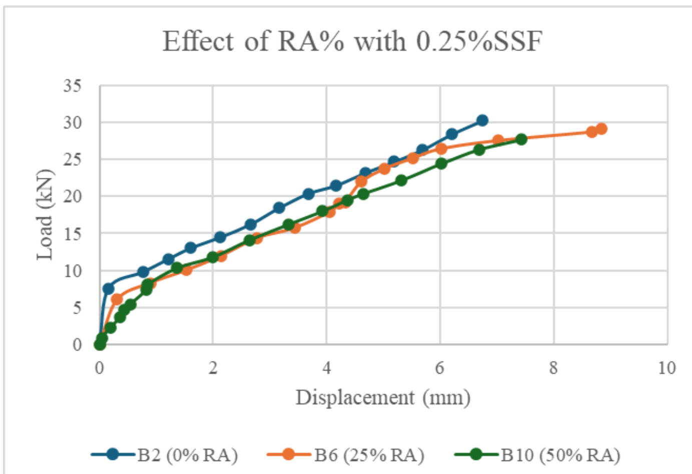


Figure 17. Effect of RA% with 0.25% SSF

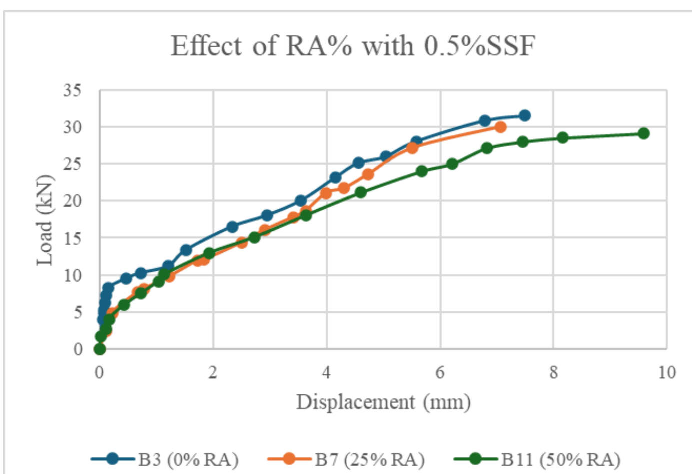


Figure 18. Effect of RA% with 0.5% SSF

Table 4 presents a comparative analysis of trial mixes TM1 to TM11, highlighting the effects of RA% and SSF% incorporation on the mechanical behavior of reinforced concrete beams. Beams produced without RA (B1-B3) consistently exhibit superior mechanical properties, including the highest compressive and splitting tensile strengths.

Beam B3 (0% RA + 0.5% SSF) demonstrates peak behavior with compressive and tensile strengths of 50 MPa and 11.2 MPa, respectively. It also achieves the highest ultimate load (31.51 kN) and a flexural efficiency ratio (P_{EX}/P_{TH}) of 1.46, indicating an agreement between experimental and theoretical load capacities. The theoretical load was calculated following BS 8110. These results reflect the beneficial role of SSF in enhancing matrix cohesion and delaying crack propagation, thereby improving both strength and toughness.

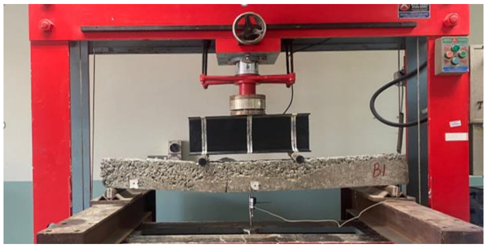
When the RA content increases to 25% (B5-B7), a marginal reduction in compressive and tensile strength is observed, due to the weaker bond and higher porosity associated with recycled aggregates. However, the negative impact is effectively mitigated by fiber inclusion. Beam B7 (25% RA + 0.5% SSF) retains a high ultimate load (29.94 kN) and achieves a P_{EX}/P_{TH} ratio of 1.40, comparable to that of the non-RA group, demonstrating the effectiveness of SSF in compensating for the inherent drawbacks of RA. The SSF enhances crack control and stress redistribution, improving the beam's overall flexural behavior despite its partially recycled content.

At 50% RA content (B9-B11), the decline in mechanical performance becomes more pronounced, particularly in B9, which contains no fiber reinforcement. This beam registers the lowest compressive strength (32 MPa) and the lowest P_{EX}/P_{TH} ratio (1.29), indicating a substantial loss in structural efficiency. In contrast, the introduction of 0.5% SSF in B11 markedly restores performance levels, raising compressive strength to 40 MPa and ultimate load to 29.15 kN. This improvement is attributed to the critical role of fibers in bridging cracks and enhancing the post-cracking behavior of concrete with high RA content.

Across all mixes, the predominant failure mode remains flexural, see Figure 19, and the deflection values at ultimate load confirm that SSF substantially improves ductility. These findings demonstrate that while higher RA content tends to degrade mechanical strength and stiffness, the addition of SSF effectively counteracts these effects by enhancing toughness and energy absorption. Consequently, fibrous reinforced RA concrete presents a viable and sustainable alternative for structural applications. Notably, the BS8110 design code does not account for the use of recycled aggregates or fiber reinforcement, emphasizing the importance of experimental research to inform future code revisions and sustainable design practices [Tawfeeq et al., 2021].

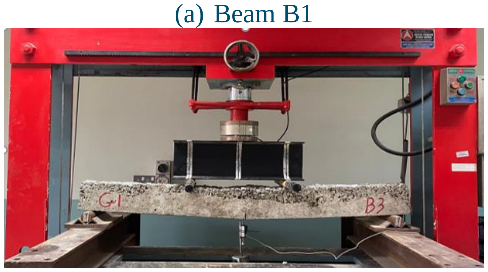
Table 4. Tests Results

Trail mix No.	Beam designation	Trial Mixes	Compressive Strength (MPa)	Ultimate Experimental (P_{EX}) [kN]	Ultimate Theo. Load (P_{TH}) [kN.m]	Yield Stress (Steel Bar) [Mpa]	$P_{EX} \backslash P_{TH}$	Deflection of the Beam at Ultimate Load [mm]	Failure Mode
TM1	B1	0%RA+0%SSF	45	30.67	21.40	460	1.43	6.82	Flexural
TM2	B2	0%RA+0.25%SSF	47	30.46	21.49	460	1.42	11.19	Flexural
TM3	B3	0%RA+0.5%SSF	50	31.51	21.62	460	1.46	7.49	Flexural
TM5	B5	25%RA+0%SSF	39	29.49	21.07	460	1.40	13.83	Flexural
TM6	B6	25%RA+0.25%SSF	42	29.21	21.25	460	1.37	8.83	Flexural
TM7	B7	25%RA+0.5%SSF	45	29.94	21.40	460	1.40	7.07	Flexural
TM9	B9	50%RA+0%SSF	32	26.56	20.53	460	1.29	10.13	Flexural
TM10	B10	50%RA+0.25%SSF	36	27.68	20.87	460	1.33	7.43	Flexural
TM11	B11	50%RA+0.5%SSF	40	29.15	21.13	460	1.38	9.58	Flexural

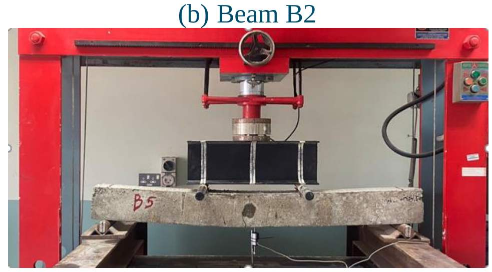


(a) Beam B1

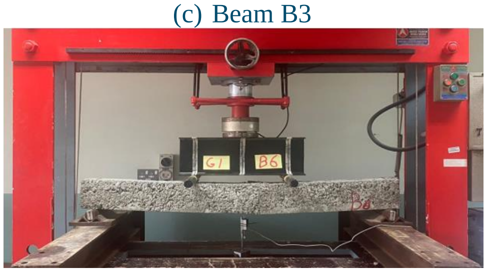
(b) Beam B2



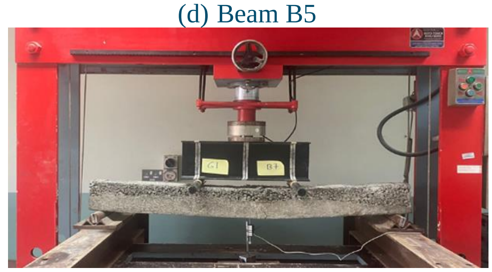
(c) Beam B3



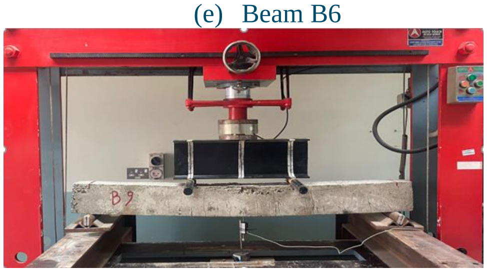
(d) Beam B5



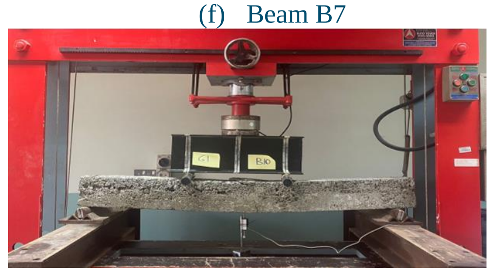
(e) Beam B6



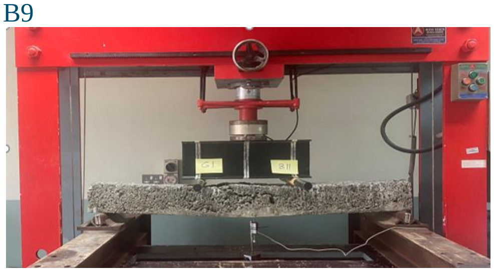
(f) Beam B7



(g) Beam B9



(h) Beam B10



(i) Beam B11

Figure 19. Failure Mode of RC Tested Beams

Conclusion

Based on the experimental results, the following conclusions can be drawn regarding the influence of stainless-steel fibers (SSF) and recycled aggregate (RA) on the flexural behavior of reinforced concrete beams:

1. Stainless-steel fibers (SSF) significantly enhance compressive strength across all recycled aggregate (RA) levels, with gains up to 25% at 50% RA using 0.5% SSF.
2. Without fibers, increasing RA content causes compressive strength reductions of up to 29% at 50% RA.
3. SSF improves tensile strength by approximately 19% to 39% across RA levels, effectively compensating for strength losses due to recycled aggregates.

4. Ductility, measured by deflection at peak load, increases by over 35% at 50% RA when SSF is incorporated.
5. Ultimate load capacity improves by up to 9.8% in beams with 50% RA reinforced with 0.5% SSF.
6. The use of recycled aggregates reduces concrete density by 2-5% at 25%-50% RA replacement, benefiting lightweight applications but necessitating fiber reinforcement to maintain mechanical properties.
7. The combined use of RA and SSF provides a sustainable solution that enhances structural performance while reducing environmental impact.

Future Work

To build upon the findings of this study, the following areas are recommended for further investigation:

1. Investigate the durability and long-term performance of reinforced concrete beams containing stainless-steel waste fibers and recycled aggregates, including resistance to chloride penetration, freeze-thaw cycles, and carbonation.
2. Explore the effects of varying fiber lengths, shapes, and dosages on the structural performance of concrete containing recycled aggregates to identify the most effective fiber characteristics for reinforcing such mixes.

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Conflict of interest: The authors declare no conflict of interest.

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