



OPEN Steel fibre-reinforced concrete with fully recycled coarse and partially recycled fine aggregates

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The construction industry is showing an increasing interest in the integration of Recycled Aggregate (RA) into concrete as a substitute for natural coarse aggregate, whether in full or in part, with the aim of reducing dependence on virgin aggregate. This shift seeks to alleviate the environmental impact associated with the extraction of aggregates from natural resources and address the environmental challenges related to concrete waste. However, there is limited research on concurrently replacing both natural fine and coarse aggregate in concrete. This study investigates the effects of substituting natural aggregates with recycled aggregate concrete, specifically using 100% recycled coarse aggregate in combination with 10% recycled fine aggregate, and further examines the influence of steel fibres on the resulting mix. Replacing natural aggregates with recycled aggregates (100% coarse, 10% fine) leads to an increase in slump value, indicating enhanced workability. However, the addition of steel fibres reduces the slump by 21.12% to 33.33%, reflecting the impact of fibre reinforcement on the mix's flow characteristics. Mechanical testing reveals that the use of recycled aggregates alone generally reduces concrete strength. Specifically, the replacement leads to reductions in compressive strength, split tensile strength, and flexural strength by 48.19%, 76.53%, and 71.96%, respectively, at 28 days. Importantly, incorporating steel fibres into the recycled aggregate concrete mitigates this strength loss, enhancing compressive strength, split tensile strength, and flexural strength by 16.51%, 6.12%, and 7.55% at the 28-day. These findings demonstrate that steel fibres effectively reinforce recycled aggregate concrete, compensating for strength reductions and improving overall performance.

Keywords Natural aggregate, Recycled aggregate, Steel fibres, Mechanical properties, Workability properties

Demolition waste as wastes arises from razed structures, however, regarding construction waste, it is defined as wastes from construction, renovation, and repairing of individual premises, commercial buildings, and other types of buildings. Construction and Demolition waste (C&DW) is defined as a material or a by-product of the construction process, that is generated due to non-conformity with the specifications, non-use or excessive utilization of resources, and damage of the resources and infrastructure and this material should be evacuated from construction site to another place or it can be utilized on construction site but rather than the initial aim of the project. It is difficult to estimate the quantities of produced C&DW and they are various in composition, however, may include concrete, bricks, dirt, stones, plaster, lumber, shingles, plumbing and electrical parts. Utilizing recycled aggregate is certainly an important step towards sustainable development in the concrete industry and the management of construction waste. Recycled aggregate (RA) is a viable alternative to natural aggregate, which helps in the preservation of the environment. One of the critical parameters that affect the use of recycled aggregate is the variability of the aggregate properties. The quality of the recycled aggregate is influenced by the quality of materials being collected and delivered to the recycling plant. In countries undergoing rapid development, management of hazardous waste materials is one of the most challenging environmental concerns. Eco-friendly materials are broadly studied these days to diminish the construction industry to save natural resources. Likewise, dumping demolition concrete waste in landfills causes capacity and environmental issues^{1,2}. Therefore, there is an urgent need to find suitable alternatives to produce concrete. Using recycled aggregate (RA) for new concrete could be an environmentally friendly solution^{3,4}.

In recent years, there has been a growing interest in the use of recycled aggregates in concrete production as a sustainable solution to manage construction and demolition waste^{5,6}. Several studies have delved into the feasibility and impact of incorporating recycled aggregates into concrete mixes. Memon and Buller⁷ tested the

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compressive strength of concrete cylinders added with various amounts of recycled coarse aggregate as alternative to natural coarse aggregate. They found that the addition of recycled coarse aggregate decreases the compressive strength particularly, when 50% of recycled coarse aggregate is added. Al-Azzawi⁸ investigated the mechanical properties of concrete made with recycled coarse aggregate as alternate and reported that the compressive and split tensile strength of concrete decreases as the replacement level increases. Baskaran et al.⁹ reported that a 50% replacement level of conventional aggregates with recycled aggregate yielded optimal concrete strength. Kessal et al.¹⁰ studied the mechanical properties of recycled aggregate concretes and found that there was a decrease in strength with higher replacement ratios. Naouaoui and Cherradi¹¹ found that compressive strength significantly reduced when the replacement level exceeded 25%, even with the addition of a superplasticizer. Also, a comprehensive exploration of the potential of recycled aggregates and various supplementary materials in enhancing concrete properties has been undertaken. Fiol et al.¹² observed that self-compacting concrete (SCC) incorporating 100% recycled aggregate exhibited reduced post-failure load-carrying capacity and showed only slight conformity with the deflection limits in long-term deflection test. Trento et al.¹³ and Hurtado-Alonso et al.¹⁴ found that incorporating 6% Recycled Crushed Wind Turbine Blade (RCWTB) significantly lowered plastic shrinkage and enhanced the flexural strength of recycled coarse aggregate concrete under moist curing, while maintaining its compressive strength. Padhi et al.¹⁵ investigated the addition of Rice Husk Ash (RHA) as a partial replacement to cement into concrete made with recycled coarse and fine aggregate. They reported that the concrete mixes contain recycled aggregate with 10–15% RHA met the essential criteria for construction applications. Brake et al.¹⁶ used sub-bituminous coal bottom ash to increase the compressive strength of the recycled aggregate concrete and achieved a 16% improvement in the compressive strength. Faysal et al.¹⁷ examined the utilisation of SCMs such as GGBS, fly ash and silica fume with the addition of superplasticizer to enhance the workability, strength and corrosion resistance of recycled aggregate concrete. Babalola et al.¹⁸ used a densified mix design approach to achieve an optimal mix proportion using various amount of GGBS. They reported that an optimal mix yielded a compressive strength of 52 MPa, which demonstrates the viability of using recycled aggregate in structural concrete. Younis et al.¹⁹ investigated the effect of metakaolin on the performance of recycled aggregate concrete and found that there was improvement in strength owing to densification of interfacial transition zone. Lesovik et al.²⁰ examined the effect of the inclusion of silica fume to recycled aggregate concrete and demonstrated the improvement in compressive strength. Javed et al.²¹ examined the impact of bagasse ash and recycled coarse aggregate on the compressive strength, which reveals the superior compressive strength. Fawzy et al.²² examined the modification of dolomite aggregate with mineral admixtures and Nano silica and demonstrated the denser microstructures and enhanced mechanical properties. RAC typically has lower tensile strength and toughness than conventional concrete due to the presence of recycled aggregates. Also, RAC is more prone to shrinkage cracking than conventional concrete due to the presence of recycled aggregates, which have a higher water absorption capacity. Fibres can help to reduce shrinkage cracking by restraining the shrinkage of the concrete. Several researchers investigated the effects of the addition of various fibres on the mechanical and durability properties of concrete^{23–25}. Xie et al.²⁶ investigated the combined addition of silica fume and fibres into recycled aggregate concrete. They demonstrated that addition of steel fibres with 10% silica fume significantly improved compressive strength by 30%. Hanumesh et al.²⁷ found that addition of 1% PP fibres can improved the compressive and tensile strength for RAC. Similarly, Yildizel et al.²⁸ examined the compressive, tensile strength and flexural strength of the foam concrete made with recycled PP fibres and aggregate. Bhan and Kaur²⁹ investigated the effect of 0.5% steel fibres on the compressive strength of concrete made with 50% of recycle coarse aggregate and they reported the addition of 0.5% of steel fibres increases the compressive strength by 20%. Lee³⁰ used 1.2 kg/m³ of nylon fibres and significantly improved the mechanical properties and permeability properties of RAC. Ghosn et al.³¹ used hemp fibres into recycled aggregate concrete and reported that the introduction of fibres mitigates the reductions in compressive strength. Gao et al.³² examined the properties of Steel Fibre-Reinforced Recycled Coarse Aggregate Concrete (SFRCAC) and reported that steel fibre volume fraction below 1.5% significantly improved the durability properties. Gao and Wang³³ examined the properties of the Steel Fiber-Reinforced Recycled Coarse Aggregate Concrete (SFRCAC) and reported that a lower fibre content of about 0.1% to 0.25% improved compressive and split tensile strength. Kaplan et al.³⁴ reported that when 50% recycled coarse aggregate (RCA) is used, the addition of 1% steel fibre produces a concrete mix with properties similar or superior that of plain conventional concrete. Ahmed et al.³⁵ investigated the High-Performance Concrete (HPC) with Coarse Recycled Aggregates (CRA) and reported that 0.1% to 0.25% RNF content enhanced compressive and split tensile strength. Kiamahalleh et al.³⁶ reported that the utilization of sugarcane fiber as replacement for fine aggregate in recycled aggregate concrete increases the compressive strength and flexural strength by 16% and 35%. Omidinasab et al.³⁷ reported that the addition of 0.5% of steel fibres into the recycled aggregate concrete increases the compressive strength and flexural strength by 89.9% and 101.45%, thus compensating for the reduced strength due to RCA. Kong et al.³⁸ investigated the effect of Hooked-end steel Fibres (HF) and Crimped steel Fibres (CF) on the mechanical properties of the RAC and found that 1.5% steel fibres significantly improved the mechanical properties. Chachar et al.³⁹ utilized steel fibres in RAC, observing that higher steel fibre percentages (1% to 5%) enhanced flexural strength significantly, compensating for the reduced strength due to 50% RCA content. Shaikh et al.⁴⁰ examined the impact of 1 mm diameter steel fibres in the 50% RCA concrete and demonstrated that 3% addition of steel fibres increased the compressive strength by 34%. Bayraktar et al.⁴¹ examined the introduction of steel fibres into the RAC and found that addition of 65 kg/m³ steel fibres of aspect ratio 55 increases flexural strength by 243.78%. Abdulhaleem et al.⁴² observed that incorporating 50% recycled aggregates along with 1% steel fibres in the concrete mix led to an approximate 20% improvement in compressive strength.

In the extensive review of existing literature, it was observed that a significant portion of studies^{9,11,43–47} have primarily focused on replacing the Natural Coarse Aggregate (NCA) with Recycled Coarse Aggregate (RCA) in the concrete. However, only few studies were focused on replacing the Natural Fine Aggregate (NFA)

Component	Values
Fineness	91.80
Standard consistency	32%
Initial setting time	69 min
Final setting time	338 min
Soundness	1 mm
Specific gravity	3.15
Compressive strength	64 N/mm ²
Silicon dioxide (SiO ₂)	22.02 (%)
Iron oxide (Fe ₂ O ₃)	5.12 (%)
Aluminium oxide (Al ₂ O ₃)	5.59 (%)
Calcium oxide (CaO)	60.84 (%)
Magnesium oxide (MgO)	1.22 (%)
Na ₂ O	0.29 (%)
K ₂ O	0.67(%)

Table 1. Physical and chemical composition of cement.

S. no	Properties	M-sand	Limitation as per IS: 2386-1963 (part III)
1	Specific gravity	2.59	2.30–2.90
2	Grading	Zone-II	–
3	Density (kN/m ³)	18.62	1280–1920
4	Fineness modulus	2.68	2.10–3.20

Table 2. Physical properties of M-sand.

with Recycled Fine Aggregate (RFA) in the concrete. Hence, this study aims to assess the effect of steel fibres on concrete made with Recycled Coarse Aggregate (RCA) and Recycled Fine Aggregate (RFA) obtained from demolition waste concrete as complete replacement for natural aggregate. This ambitious research initiative aims to push the boundaries of sustainable construction practices and contribute valuable insights into the utilization of recycled materials for concrete production.

Material and methodology

Materials

In this research work, the materials like cement, fine and coarse aggregate, fly ash, super plasticizer, and steel fibre were used to make sample block for bond strength testing. The concrete for all specimens was of ordinary strength. Ordinary Portland Cement (OPC) of grade 53 complying to IS 12269-2015 was used. M-Sand that belongs to Zone-II according to IS-383 specification was used as a fine aggregate. The coarse aggregate utilized complied with IS: 383-1970⁴⁸. The concrete was mixed with potable water. To achieve workability of concrete mixes with low water to binder ratio, a superplasticizer based on Polycarboxylate ether-based superplasticizer was utilized, and it complies with ASTM C 494-13⁴⁹.

Cement

The physical and chemical composition of the cement was presented in Table 1.

Fine aggregate

In the current investigation, the fine aggregate for the concrete mix was acquired through the crushing of rock to create M-sand. The M-sand utilized in the research complies with the zone-II classification outlined in IS: 383-2016. The M-sand particles exhibit a size range spanning from 150 microns to 4.75 mm, satisfying the quality benchmarks set by IS. Detailed information concerning the physical properties of the M-sand can be found in Table 2.

The recorded values were within the acceptable range as specified in IS 383:2016. Additionally, the density values of the M-sand complied with the limits set by relevant codes. However, it's essential to highlight that the M-sand utilized in this study fell under zone-II and displayed various fineness modulus values, all of which were within the acceptable range. A thorough sieve analysis was conducted to comprehensively evaluate the grading pattern of the aggregates. The findings revealed a close similarity in the shape of the M-sand samples. For detailed information on the percentage passing values and corresponding grading for M-sand, please refer to Table 3.

The characteristics of the aggregate, encompassing geometry, physicality, and chemistry, are generally contingent upon the water absorption rate of the aggregate. An overabundance of water added to the concrete mix has adverse impacts on both the mechanical and durability properties of the concrete. Conversely, inadequate

S. no	Sieve size	Passing (%)	Limitation as per IS: 383-2016
		M-sand	
1	4.75 mm	100	90–100
2	2.36 mm	90.70	75–100
3	1.18 mm	66.20	55–90
4	600 µm	39.80	35–59
5	300 µm	25.50	8–30
6	150 µm	9.90	0–10

Table 3. Sieve analysis of M-sand.

S. no	Types	Water absorption rate, %	Limitation as per IS: 1124 -1974
1	M-sand	0.50	2%

Table 4. Water absorption rate of fine aggregate.

S. no	Characteristics	Values	Limitation as per IS
1	Specific gravity	2.83	IS: 2386 (Part 3): 2016
2	Density (kN/m ³)	26.50	IS: 2386 (Part 3): 2016
3	Crushing value	18.80	IS: 2386 (Part 4): 2015
4	Fineness modulus	6.50	IS: 383: 2016
5	Impact value	13.50	IS: 2386 (Part 4): 2015
6	Shape	Angular	IS: 383: 2016

Table 5. Characteristics of coarse aggregate.

S. no	IS sieve designation (mm)	Percentage of passing	IS recommended range
1	12.50	87.70	85–100
2	10.00	39.70	0–45
3	4.75	0.00	0–10

Table 6. Sieve analysis of coarse aggregate.

water addition results in the incomplete hydration of the concrete. Therefore, it is imperative to incorporate the appropriate amount of water into the concrete mix. The M-sand water absorption rate was identified to be within the acceptable threshold of not exceeding 2%, in accordance with the specifications outlined in IS: 1124-1974. The water absorption rate data for the aggregate is detailed in Table 4.

Coarse aggregates

This study employed coarse aggregate that complies with the standards specified in IS: 383-2016. The physical characteristics of the coarse aggregate were assessed in accordance with IS: 2386-1963 (Part-III). Angular granite stones, well-graded and with a maximum size of 12.5 mm, were employed in this study, adhering to the standards set by IS: 383-1970. The specific gravity of the stones was measured at 2.7, the fineness modulus at 7.2, and the water absorption rate at 0.62%. The concrete mix in this investigation comprised 60% of 20 mm size aggregate and 40% of 12 mm size aggregate. Extensive testing demonstrated that the physical properties of the coarse aggregate met the acceptable criteria, as detailed in Table 5. The sieve analysis of the coarse aggregate sample is also provided in Table 6.

Super plasticizer

Superplasticizer, a brown liquid easily mixable with water, is formulated with specially processed lignosulphonate additives. In concrete construction, preventing water penetration through capillary pores is vital, as even well-constructed concrete structures exhibit some degree of porosity. The presence of water in hardened concrete can lead to reinforcement corrosion, especially in concrete prone to moisture absorption during freeze–thaw cycles. If the infiltrating water carries aggressive dissolved salts, it can contribute to additional deterioration. Classic Crete Superflo-SP superplasticizer addresses these concerns by filling remaining pores due to slow evaporation of excess water, not consumed during cement hydration. Additionally, it introduces a controlled amount of air without increasing the dosage, reducing capillary suction by blocking pores. The plasticizing

S. no	Contents	Unit	Test value
1	Specific gravity	-	1.170 ± 0.015 at 27 °C
2	Total solids	%	45
3	Chloride	%	Nil
4	Air entrainment	%	Up to 2% additional air
5	Appearance	–	Brown liquid

Table 7. Properties of super plasticizer.

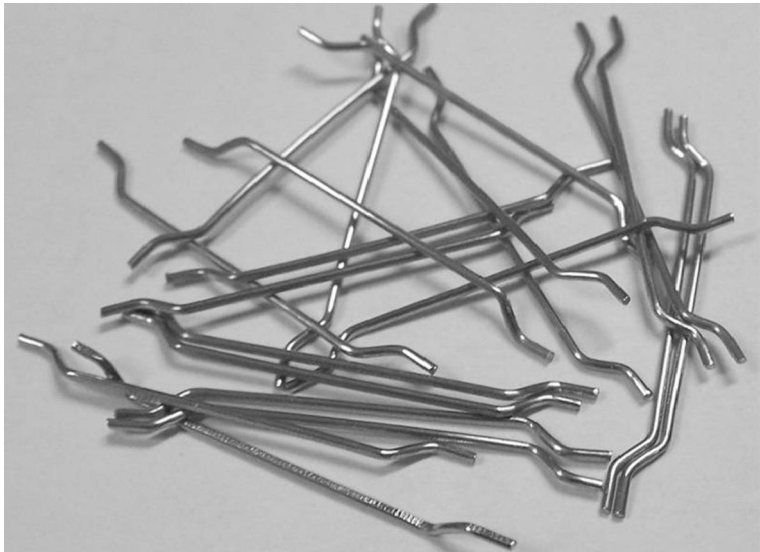


Fig. 1. Steel fibre.

action of the superplasticizer helps produce denser concrete mortar, significantly reducing permeability. The commercially available Classic Crete Superflo-SP superplasticizer, used in this study, adheres to IS: 2645-2003 standards, displaying a specific gravity of 1.24, no chloride content, and a solid content of 48%. The addition of superplasticizer improves concrete workability, with the slump value increasing as the dosage of superplasticizer rises. Typically, the addition of superplasticizer ranges from 0.20 to 0.32 L per 100 kg of cement. Table 7 outlines the general properties of the superplasticizer employed in this research.

Steel fibres

In this research, hooked end steel fibres adhering to the specifications outlined in ASTM A820-01⁵⁰ were employed. Majority of existing studies^{51–53} reported that the 2% volume fraction of the steel fibres was optimum for used in concrete. Accordingly, the volume fraction of the steel fibres utilized in this study ranged from 0.5% to 2%. The inclusion of steel fibres in the concrete mix aimed to reduce cracking and enhance the concrete’s durability. Specifically, hook-end steel fibre was employed, known for their wavy configuration along their length added as volume fraction of 0.5 as shown in Fig. 1. Table 8 provides details on the length, diameter, and aspect ratio of the fibres.

Mix proportioning

The formulation of the M25 grade concrete mix adhered to the IS: 10262-2019⁵⁴ guidelines to achieve the targeted concrete strength. After conducting several trial mixes that involved the inclusion of recycled aggregate, an optimized mix was developed, yielding the specified strength as outlined in Table 9. Employing these optimized ratios, concrete mixes were prepared for evaluating their workability and mechanical properties. During the mixing process, recycled coarse aggregate and fine aggregate were initially introduced into the mixer and blended for a duration of 2 min. Following this, the requisite amount of cement was added to the mixture and mixed for an additional 2 min under dry conditions. Subsequently, steel fibre was incorporated. Finally, the water and superplasticizer mixture were introduced into the mixer and blended for a period of 4 min.

Experimental investigation

The main objective of this study is to assess the influence of adding steel fiber to recycled fine and coarse aggregate concrete. The workability and mechanical properties of steel fiber in recycled aggregate concrete were compared with those of conventional concrete, aiming to determine the optimal concrete mix performance.

Properties	Hook end steel fibre
Density	7680 kg/m ³
Material	Low carbon drawn round wire
Tensile strength	1300 MPa
Elastic modulus	200 GPa
Specific gravity	7.9
Length	50 mm
Diameter	1 mm
Aspect ratio	50
ASTM specs	ASTM A820 M04 type 1
Appearance and form	Clear, bright and undulated along the length

Table 8. Properties of steel fibre.

Composition	M1 (control Mix)	M2 (100% RCA 10% RFA)	M3 (100% RCA 10% RFA + 0.5% SF)	M4 (100% RCA 10% RFA + 1% SF)	M5 (100% RCA 10% RFA + 1.5% SF)	M6 (100% RCA 10% RFA + 2% SF)
Cement (kg/m ³)	342.1	342.1	342.1	342.1	342.1	342.1
Water (lt/m ³)	143.68	143.68	143.68	143.68	143.68	143.68
Natural fine Aggregate (kg/m ³)	699.31	629.41	629.41	629.41	629.41	629.41
Natural coarse Aggregate (kg/m ³)	1223.89	–	–	–	–	–
Recycled fine aggregate (kg/m ³)	–	69.9	69.9	69.9	69.9	69.9
Recycled coarse aggregate (kg/m ³)	–	1223.89	1223.89	1223.89	1223.89	1223.89
Steel fibre (kg/m ³)	–	–	1.71	3.42	5.13	6.84
Super Plasticizer (kg/m ³)	3.42	3.42	3.42	3.42	3.42	3.42

Table 9. Optimized mix proportion for M25 grade concrete. *RCA* recycled coarse aggregate, *RFA* recycled fine aggregate, *SF* steel fibre.

Workability

Workability, referring to the ease of placing freshly mixed concrete while preventing segregation, is commonly assessed using the slump cone test. To determine the slump value of different concrete mixes (M1, M2, M3, M4, M5, and M6), experiments were conducted following the guidelines outlined in IS: 1199-1959⁵⁵. The slump values of fresh concrete, obtained through the slump cone test, are depicted in Fig. 2.

Preparations of specimens

The preparation of the designed mix during the concrete mixing process involved careful consideration of mixing proportions and material preparation to achieve a uniform and homogeneous mixture. Cement, M-sand, and coarse aggregates were precisely dried in a tray to ensure even colour and eliminate any cement clusters or moisture from the sand. Once the required amounts of cement, M-sand, and coarse aggregate were weighed, a thorough dry mixing process was executed. The combination of coarse and fine aggregates with cement was precisely blended until a completely homogeneous mixture was achieved. The addition of water followed a systematic approach, with 50 percent added to the dry concrete mix and thoroughly mixed. Subsequently, 40 percent water and superplasticizer were incorporated into the wet mixture.

Finally, the remaining 10 percent of water was added, and the concrete mixer was used to ensure a consistent and homogeneous mix. Prior to casting concrete samples, meticulous cleaning and oiling of the required moulds were carried out. Immediately after mixing and assessing fresh concrete properties, such as slump and concrete temperature, the concrete samples were cast, completing the systematic and precise process. External vibration was applied using a table vibrator for proper compaction of concrete. The specimens were allowed to cure for about 28 days, after which the corresponding mechanical tests, including compression, split tensile and flexural strength were conducted on the concrete specimens. The specimens illustrated in Figs. 3, 4, 5, and 6 were cast using steel moulds, adhering to the prescribed standards (IS: 516-1959 and IS: 5816-1999).

Compressive strength test

The assessment of compressive strength for concrete mixes M1, M2, M3, M4, M5, M6, and M7 utilized the compression test. Specimens in the form of 100 mm cubes were cast and examined after 28 days of curing, employing a UTM with a 2000kN capacity, following the guidelines of IS: 516–1959, as depicted in Fig. 7.



Fig. 2. Slump test.



Fig. 3. Steel fibre reinforced concrete.

Split tensile strength test

The split tensile test was employed to assess the compressive tensile strength of the M1, M2, M3, M4, M5, and M6 concrete mixes. Test samples in the form of 300 mm height and 150 mm diameter cylinders were cast and examined after 28 days of curing, utilizing the UTM with a 2000 kN capacity in accordance with the IS: 5816–1959 standards, as depicted in Fig. 8.

Flexural strength test

The flexural strength of the M1, M2, M3, M4, M5, and M6 concrete mixes was evaluated using the flexural test. After a 28-day curing period, prism-shaped test samples measuring 150 × 150 × 750 mm were subjected to testing by placing them in a UTM with a capacity of 2000 kN under a single-point loading system, with a simply



Fig. 4. Casting of the concrete.



Fig. 5. Curing in progress.



Fig. 6. Cube, cylinder and prism specimens.



Fig. 7. Compressive strength test setup.



Fig. 8. Split tensile strength test setup.

supported span of 650 mm. Loading was applied gradually until the test specimen experienced complete failure. The testing procedure followed the IS: 5816–1959 standards, as depicted in Fig. 9.

Test results and discussions

Workability properties of recycled aggregate concrete

Figure 10 depicts the variations in slump values among different mixes of recycled aggregate concrete, underscoring the need for careful consideration of workability factors when utilizing recycled aggregates. Managing this dynamic aspect is essential to achieve an optimal balance between sustainability goals and the practical requirements of workable concrete mixtures.

In the control concrete mix (M1), where natural aggregate is utilized, the slump value is measured at 150 mm. Complete replacement (100%) of natural coarse aggregate with recycled coarse aggregate, along with a partial replacement (10%) of natural fine aggregate with recycled fine aggregate, leads to a 17.85% increase in the slump value. This increment in slump may be attributed to the porosity of the recycled aggregate, affecting the water demand in the concrete mix. The higher porosity facilitates better water distribution and lubrication, contributing to enhanced workability, as suggested by Tam et al. in 2008. The introduction of steel fibers into recycled aggregate concrete results in a reduction in slump values. Specifically, the addition of 0.5%, 1%, 1.5%, and 2% of hooked end steel fibers leads to slump reductions of 21.12%, 24.24%, 30.30%, and 33.33%, respectively. The incorporation of steel fibers acts as reinforcement within the concrete mix, forming a network that hampers the free flow and, consequently, reduces slump. Studies by Hung et al.⁵⁶, Uygunoglu⁵⁷ and Mohammed et al.⁵⁸ reported that higher fibre content results in a more pronounced reduction in slump value. In this study, the



Fig. 9. Flexural strength test setup.

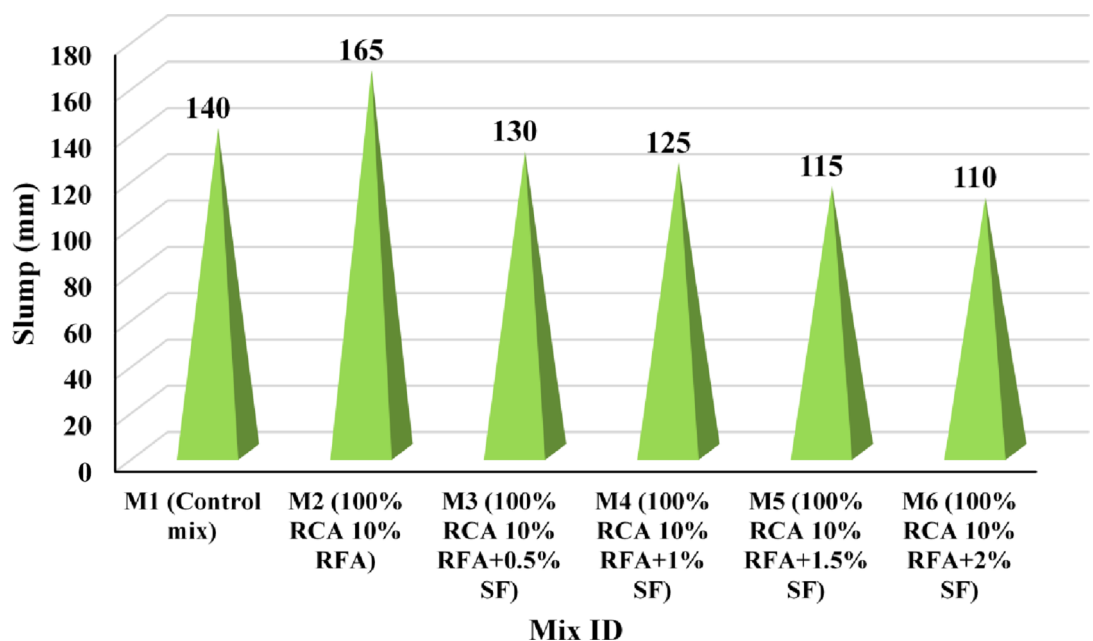


Fig. 10. Variation of slump value of control and recycled aggregate concrete mixes.

addition of a higher fibre content of 2% reduces the slump value of recycled aggregate concrete by 33.33%. However, it is important to note that the slump values of the developed mixes still fall within the category of high and very high workability, according to IS: 1199–2018 and IS: 456-2000⁵⁹.

Compressive strength of recycled aggregate concrete

Figure 11 displays the compressive strength results for the control concrete, recycled aggregate-added concrete, and recycled aggregate with steel fibre-added concrete at 7, 14, and 28 days of curing.

It is noted that the complete replacement of natural coarse aggregate with recycled coarse aggregate leads to a decline in compressive strength. Similarly, the partial substitution of natural fine aggregate with recycled fine aggregate also results in reduced compressive strength. Conversely, the introduction of steel fibres into recycled aggregate concrete contributes to an increase in compressive strength. The complete replacement of natural coarse aggregate with recycled coarse aggregate, combined with the partial replacement of natural fine aggregate with recycled fine aggregate, results in a decrease in compressive strength by 21.79%, 27.62%, and 48.19% at 7, 14, and 28 days, respectively. Concrete strength is notably affected by the Interfacial Transition Zone (ITZ) between the cement paste and particles. Recycled aggregates may introduce a weaker ITZ, leading to diminished bond strength and consequently lower compressive strength⁶⁰. The addition of steel fibres into recycled aggregate

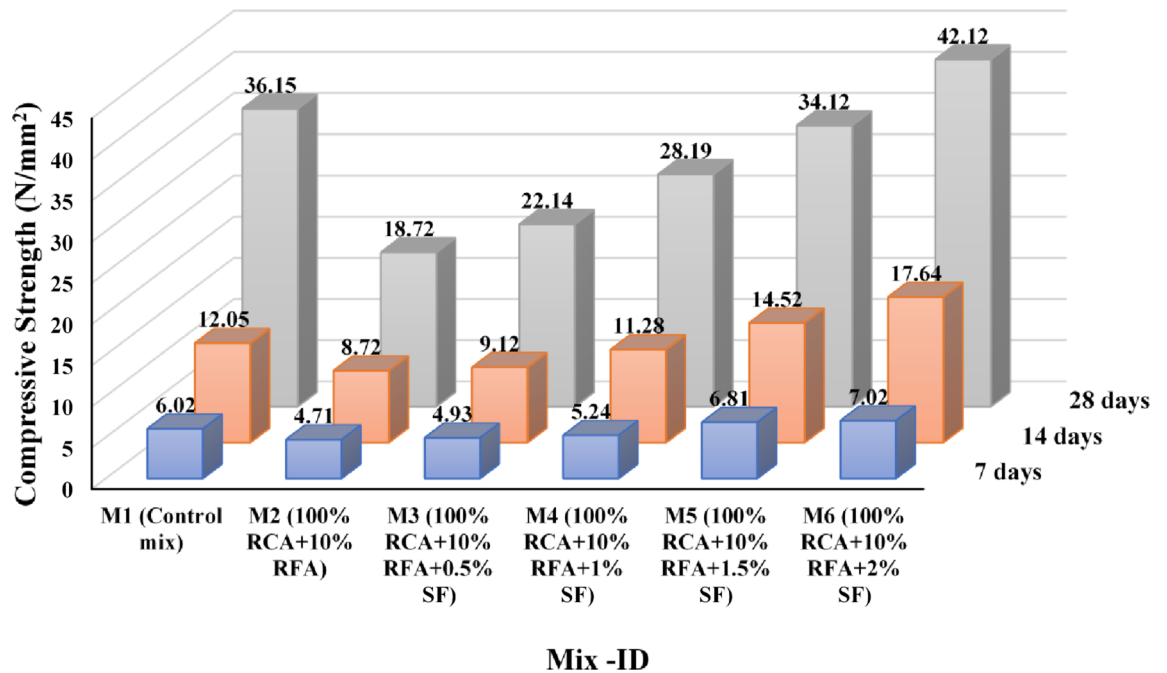


Fig. 11. Variation of compressive strength of control and recycled aggregate concrete mixes.

concrete gradually enhances compressive strength. Literature suggests that an even distribution of steel fibers within concrete can improve ductility and durability. This enhanced ductility proves beneficial in resisting compressive stresses and preventing unexpected brittle failure⁶¹. Specifically, the incorporation of 0.5%, 1%, 1.5%, and 2% of steel fibres into recycled aggregate concrete results in incremental increases in compressive strength: 4.67%, 11.25%, 44.58%, and 49% at 7 days, 4.5%, 29.35%, 66.51%, and 100% at 14 days, and 18.26%, 50.58%, 82.26%, and 125% at 28 days. The introduction of 2% steel fibres into recycled aggregate concrete (100% recycled coarse aggregate with 10% recycled fine aggregate) resulted in achieving a compressive strength higher than that of the natural aggregate concrete (control mix). The compressive strength of the recycled aggregate concrete, enhanced with 2% steel fibres, exceeded that of the natural aggregate concrete (control mix) by approximately 16.51%. Unlike Natural Aggregate Concrete (NAC), recycled aggregates may exhibit rougher surfaces due to the presence of old mortar, fostering a stronger mechanical bond between the aggregate and the new cement paste. This reinforced connection has the potential to influence compressive strength by facilitating more effective load transmission within the concrete matrix. In a study by Adnan et al.⁶², a 22.3% decrease in compressive strength was reported with the complete replacement of natural aggregate with recycled aggregate. Shawais et al.⁶³ demonstrated that incorporating 0.44% steel fibres into concrete mitigated the 9% reduction in compressive strength observed when natural coarse aggregate was completely replaced with recycled aggregate. However, in this study, the compressive strength increased by 16.51% with the replacement of 100% natural coarse aggregate with recycled coarse aggregate and 100% natural fine aggregate with recycled fine aggregate, along with the addition of 2% steel fibres. In a study conducted by Aslani et al.⁶⁴, a compressive strength of only 43.82 MPa was achieved with a 40% replacement of natural aggregate with recycled aggregate. Conversely, in the current study, a compressive strength of 42.12 MPa was attained with the complete replacement of natural coarse aggregate with recycled coarse aggregate, along with 10% natural fine aggregate replaced by recycled fine aggregate.

Split tensile strength of recycled aggregate concrete

Figure 12 illustrate the split tensile strength outcomes for the control concrete, recycled aggregate-added concrete, and recycled aggregate with steel fibre-added concrete at 7, 14, and 28 days of curing.

It is evident that the complete substitution of natural coarse aggregate with recycled coarse aggregate results in a decline in split tensile strength. Similarly, the partial replacement of natural fine aggregate with recycled fine aggregate also leads to diminished split tensile strength. However, the introduction of steel fibres into recycled aggregate concrete contributes to an augmentation in split tensile strength. In general, recycled aggregate often exhibits higher water absorption capacities than natural aggregate, potentially resulting in increased water demand during mixing. This factor can impact the cement-to-water ratio and subsequently influence strength⁶⁵. Consequently, the complete replacement of natural coarse aggregate with recycled coarse aggregate, coupled with the partial replacement of natural fine aggregate with recycled fine aggregate, leads to a reduction in split tensile strength by 50.7%, 76.92%, and 76.53% at 7, 14, and 28 days, respectively. The inclusion of steel fibres into recycled aggregate concrete progressively enhances split tensile strength. Specifically, the integration of 0.5%, 1%, 1.5%, and 2% of steel fibres into recycled aggregate concrete results in incremental increases in split tensile strength by 31.25%, 59.37%, 96.81%, and 118% at 7 days, 83.33%, 210%, 320%, and 360% at 14 days; and 81.52%, 205.43%, 310.81%, and 352% at 28 days. The split tensile strength of recycled aggregate concrete (100% recycled

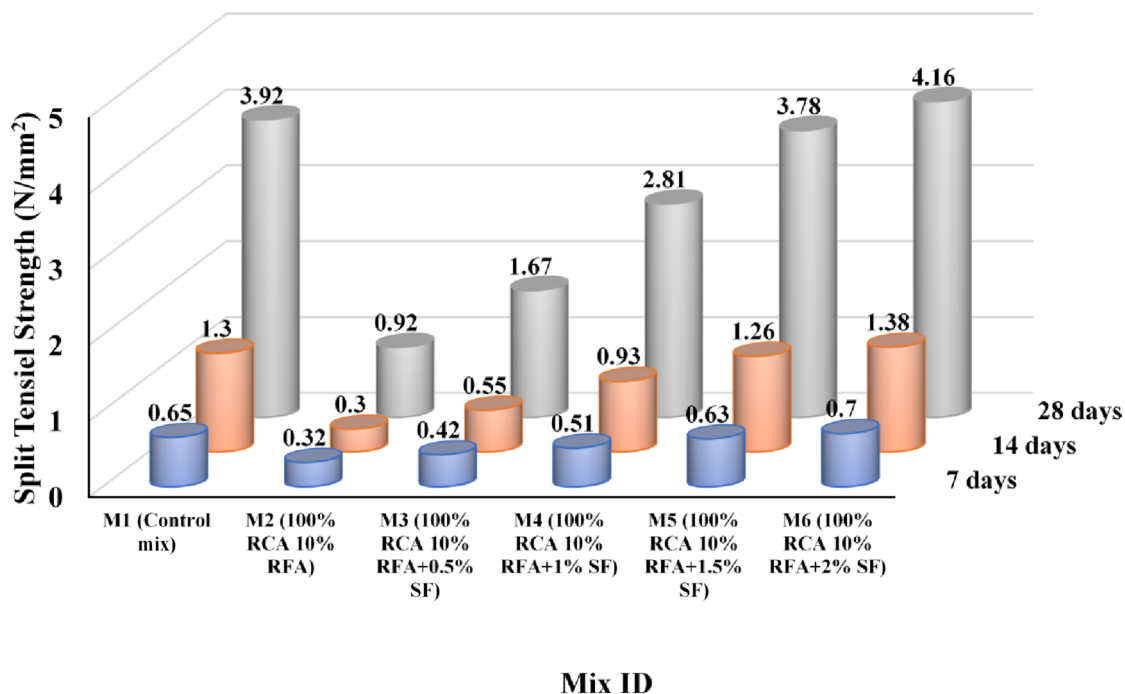


Fig. 12. Variation of split tensile strength of control and recycled aggregate concrete mixes.

coarse aggregate with 10% recycled fine aggregate) with the addition of 2% steel fibres can surpass the strength of natural aggregate concrete (control mix). Specifically, the split tensile strength of recycled aggregate concrete with 2% steel fibres was approximately 6.12% higher than that of the natural aggregate concrete (control mix). However, Shawais et al.⁶³ demonstrated that incorporating 0.44% steel fibres into concrete causes 40% reduction in tensile strength when natural coarse aggregate was completely replaced with recycled aggregate.

Flexural strength of recycled aggregate concrete

Figure 13 depicts the flexural strength of the control concrete, recycled aggregate-added concrete, and recycled aggregate with steel fibre-added concrete at 7, 14, and 28 days of curing.

It is evident that the complete replacement of natural coarse aggregate with recycled coarse aggregate leads to a decrease in flexural strength. Similarly, the partial replacement of natural fine aggregate with recycled fine aggregate also results in reduced flexural strength. However, the addition of steel fibres into recycled aggregate concrete contributes to an increase in flexural strength. In general, the strength of concrete is significantly influenced by the Interfacial Transition Zone (ITZ) between the cement paste and the particles. Recycled aggregates may have a weaker ITZ, resulting in reduced bond strength and consequently a decrease in flexural strength⁶⁰. The addition of steel fibres into recycled aggregate concrete progressively enhances flexural strength. Specifically, the incorporation of 0.5%, 1%, 1.5%, and 2% of steel fibres into recycled aggregate concrete results in incremental increases in flexural strength by 68.42%, 115.7%, 189.47%, and 273.64% at 7 days; 72.97%, 75.67%, 227%, and 283.73% at 14 days; and 72.97%, 117.1%, 185.55% and 282.88% at 28 days. It was observed that the addition of 2% steel fibres into the recycled aggregate concrete (100% recycled coarse aggregate with 10% recycled fine aggregate) can achieve a flexural strength higher than that of the natural aggregate concrete (control mix). Specifically, the flexural strength of recycled aggregate concrete with 2% steel fibres was approximately 7.55% higher than that of the natural aggregate concrete (control mix). This is attributed to the weaker characteristics of recycled aggregate due to micro-cracks or pre-existing damage, which the steel fibres compensate for by providing additional reinforcement and bridging internal micro-cracks.

Conclusions

This study explores the consequences of replacing natural aggregate with recycled aggregate concrete, specifically utilizing 100% recycled coarse aggregate and 10% recycled fine aggregate, in addition to the introduction of steel fibres. The resulting conclusions drawn from this investigation include:

- The replacement of natural aggregate with recycled aggregate concrete (100% recycled coarse aggregate with 10% recycled fine aggregate) increases the slump value by 17.85% primarily due to the higher porosity of recycled aggregate and residual mortar content of recycled aggregates, which enhanced water absorption and created excess free water, thereby improving workability. However, addition of steel fibres into the recycled aggregate concrete decreases the slump value in the range of 21.12% to 33.33%. Inclusion of steel fibres into recycled aggregate concrete hinders free flow of concrete, thus reduces slump.

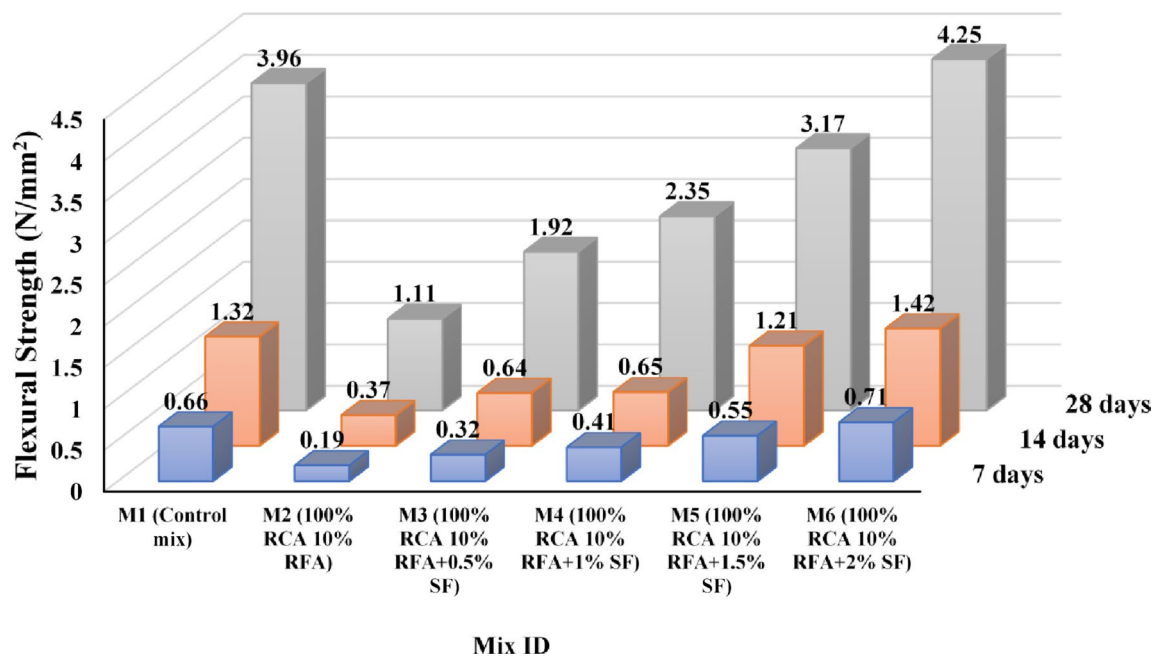


Fig. 13. Variation of flexural strength of control and recycled aggregate concrete mixes.

- The replacement of natural aggregate with recycled aggregate concrete (100% recycled coarse aggregate with 10% recycled fine aggregate) reduces compressive strength by 21.79%, 27.62%, and 48.19% at 7, 14 and 28 days. This decline can be attributed to the weaker Interfacial Transition Zone (ITZ) of recycled aggregates, the presence of adhered mortar, and pre-existing microcracks, which collectively reduced bond quality and load transfer efficiency within the matrix.
- The replacement of natural aggregate with recycled aggregate concrete (100% recycled coarse aggregate with 10% recycled fine aggregate) reduces decreases split tensile strength by 50.7%, 76.92%, and 76.53% as well as flexural strength by 71.2%, 71.9%, and 71.96% at 7, 14 and 28 days.
- Despite the inherent weakness of recycled aggregates, the addition of steel fibres progressively enhanced compressive, tensile, and flexural strengths by 16.51%, 6.12%, and 7.55% at 28 days. This improvement is explained by fibre bridging, which arrests microcrack propagation, improves stress distribution, and increases ductility. At higher dosages (2% steel fibre), the recycled aggregate concrete surpassed the strength of the natural aggregate control mix, demonstrating the effectiveness of fibre reinforcement in counteracting ITZ deficiencies.
- Specifically, flexural and tensile strength gains were particularly pronounced because fibre bridging provides direct resistance against crack opening, while compressive strength improvements were linked to the enhanced confinement effect provided by uniformly dispersed fibres, preventing brittle failure and improving ductility.
- While recycled aggregates tend to reduce strength due to their weaker microstructural characteristics, the incorporation of steel fibres compensates for these drawbacks by enhancing crack resistance and load redistribution, ultimately leading to superior performance compared to the control mix.

Data availability

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

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Author contributions

Saravanan M: Conceptualization, methodology, data collection, formal analysis, writing – original draft preparation. Dr. Nirmala R: Supervision, writing – review and editing, validation, project administration. Both authors have read and approved the final manuscript.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

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