Experimental Investigation on the Strength Behavior of Hybrid Fibre-Reinforced Recycled Aggregate Concrete

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Abstract. The study provides a systematic experimental examination of mechanical and durability performance of hybrid fibre reinforced recycled aggregate concrete (HFRRAC). The mix was prepared by replacing natural coarse aggregate with recycled coarse aggregate (RCA) as a partial replacement at the percentage levels of 0%, 10%,20%,30%,40% and 50% respectively by volume corresponding to M25 grade. A hybrid mix of polypropylene and nylon fibres were added at total fibre contents of 0.5%, 1.0% and 1.5% by volume to the concrete. The microstructural observations indicated the good physical and mechanical characteristics of the optimized blend, which were confirmed using compressive strength, split tensile strength and flexural strength tests for the mechanical properties, while water absorption and acid resistance tests exhibited their durability characteristics. The results show that the increased RCA reduces strength, but addition of hybrid fibres compensates for this reduction effectively. Based on the tests, optimum performance was obtained with 30% RCA replacement and hybrid fibre content of 1% (0.5% polypropylene + 0.5% nylon); 28 day compressive strength exceeding 25 MPa with significant increases in tensile and flexural strength also observed. Durability analysis indicated lower water absorption and enhanced acid attack resistance for the fibre reinforced mixtures. The results show that with optimized RCA and hybrid fibre content HFRRAC can be a durable sustainable alternative of conventional concrete and can provide necessary contribution towards conservation of resources and circular economy based construction practices.

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1 Introduction

Due to the fast infrastructure growth, there is a significant increase in construction and demolition waste, which poses environmental issues such as i) disposal problems and ii) depletion of natural resources [1]. As one of the most used construction materials, concrete requires high amounts of natural aggregates and is responsible for a major part of environmental pollution. The application of produced RCA from demolished concrete structures serves as an effective way to reduce natural aggregate consumption and decrease the construction waste.

In addition to these environmental advantages, the two main features of recycled aggregate concrete knew-up, namely mechanical and durability properties exhibit lower performance strengths than traditional concrete. [2]. This reduction in performance is mainly attributed to the presence of adhered old mortar, recycled aggregates increased water absorption and porosity [3]. These limitations restrict the extensive use of concrete with recycled aggregate in structural elements unless suitable performance enhancement techniques are adopted [4].

Fibre reinforcement has been widely recognized as an effective method for improving the structural performance of concrete. Fibres enhance crack resistance, tensile strength, post-cracking behavior and the ability to absorb energy [5,6]. Hybrid fibre systems, which combine two different types of fibres, have gained increasing attention due to their synergistic contribution to concrete performance [9]. Polypropylene fibres are particularly effective in controlling micro-cracks and plastic shrinkage, while nylon fibres enhance toughness and tensile strength [10].

Although several studies have investigated fibre-reinforced recycled aggregate concrete, limited experimental research is available on the combined use of polypropylene and nylon fibres with systematic optimization of fibre dosage and RCA replacement levels for structural-grade concrete [11]. Therefore, the present study aims to identify an optimum combination of RCA content and hybrid fibre dosage for M25 grade concrete by evaluating mechanical strength and durability characteristics. The outcomes of this research provide practical guidance for the development of sustainable concrete materials suitable for structural applications.

2 Materials and Methods

The 53-grade Ordinary Portland Cement (OPC) used complied with IS 12269:2013 [7]. Crushed demolished concrete was used to make recycled coarse aggregate, which was then processed to a maximum size of 20 mm. Natural coarse aggregate and river sand conforming to IS 383:2016 were used. Hybrid fibres consisted of polypropylene and nylon fibres of 12–15 mm length. Potable water conforming to IS 456:2000 was used for mixing and curing.

2.1 Cement

This study used ordinary Portland cement (OPC) of grade 53 that complied with IS 12269:2013. The cement was stored in a dry environment, and its physical properties were tested as per relevant Indian Standards.

2.2 Recycled Coarse Aggregate (RCA)

Recycled coarse aggregate was obtained from crushed concrete debris collected from demolished buildings as shown in Fig 1. The material was cleaned, crushed, and sieved to obtain a maximum aggregate size of 20 mm. The physical properties of RCA were evaluated and found to be suitable for structural concrete applications.

Fig. 1. Recycled Aggregate

2.3 Natural Coarse Aggregate (NCA)

Natural coarse aggregate consisting of crushed granite stone and river sand conforming to IS 383:2016 [8] were used as coarse and fine aggregates, respectively.

2.4 Fine Aggregate

The fine aggregate was river sand that complied with Zone II of IS 383:2016 standards. After being cleaned and dried, the sand's specific gravity (2.62), fineness modulus (2.8), and water absorption (1.2%) were measured.

2.5 Hybrid Fibres

Hybrid fibres used in this study consisted of polypropylene and nylon fibres with lengths ranging from 12 to 15 mm. The fibres were added in equal proportions to form the hybrid fibre system. Potable tap water conforming to IS 456:2000 was used for mixing and curing.

2.6 Water

During mixing and curing, potable tap water that complied with IS 456:2000 was used, with a pH of 6.5 to 7.5.

2.7 Mix Design and Proportioning

For M25 grade concrete, concrete mixes were created in compliance with IS 10262:2019. A water–cement ratio of 0.50 was adopted to achieve the required workability and strength. A nominal mix ratio of 1:1.5:3 (cement:fine aggregate:coarse aggregate) is reported for reference.

Six concrete mixes were prepared by replacing natural coarse aggregate with recycled coarse aggregate at 0%, 10%, 20%, 30%, 40%, and 50% by volume. For each RCA replacement level, hybrid fibres were incorporated at 0.5%, 1.0%, and 1.5% by volume of concrete to evaluate the influence of fibre dosage as shown in Fig 2. Table 1 presents the mix proportions used in the study.

Table 1. Mix Proportions

Mix ID	RCA replacement (%)	Cement (kg/m³)	Fine aggregate (kg/m³)	Natural coarse aggregate (kg/m³)	Recycled coarse aggregate (kg/m³)	Water (kg/m³)	Fibre content (%)
Control	0	394	591	1182	0	197	0, 0.5, 1.0, 1.5
Mix-1	10	394	591	1064	118	197	0, 0.5, 1.0, 1.5
Mix-2	20	394	591	946	236	197	0, 0.5, 1.0, 1.5
Mix-3	30	394	591	828	354	197	0, 0.5, 1.0, 1.5
Mix-4	40	394	591	709	473	197	0, 0.5, 1.0, 1.5
Mix-5	50	394	591	591	591	197	0, 0.5, 1.0, 1.5

*Three specimens were tested for each mix and each test, and average values are reported.

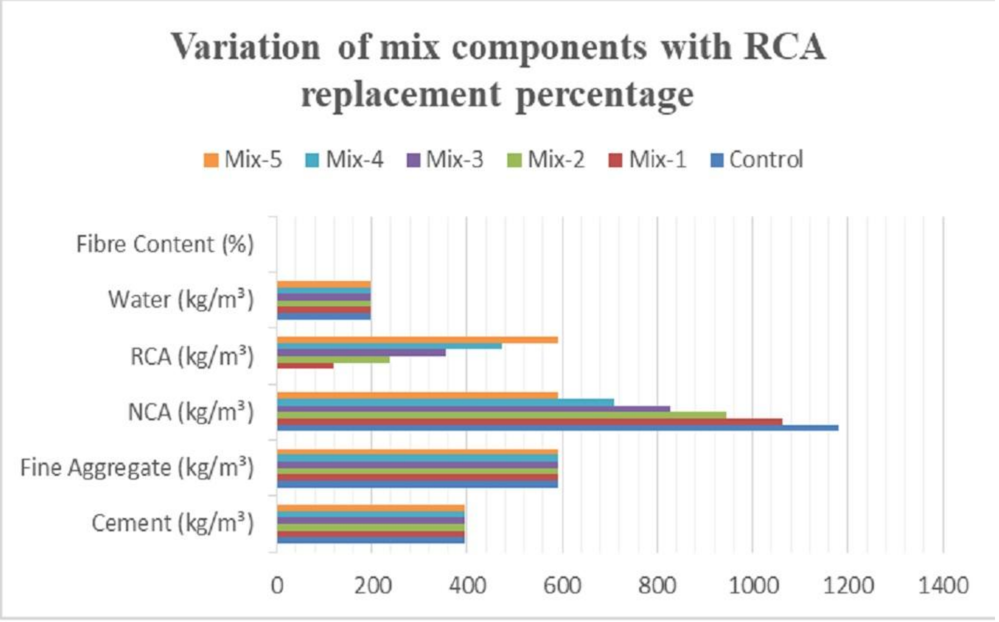

Fig. 2. Variation of mix components with RCA replacement percentage

2.8 Mixing and Curing Procedure

Concrete mixing was carried out using a mechanical pan mixer. Dry materials were mixed first to ensure uniform distribution of fibres, followed by the addition of water as shown in Fig 3. Cubes (150 × 150 × 150 mm), cylinders (150 mm diameter × 300 mm height), and prisms (100 × 100 × 500 mm) were cast for compressive, split tensile, and flexural strength tests, respectively. Three specimens were tested for each mix and test condition. Specimens were cured in water at 27 ± 2 °C until the testing age.

Fig. 3. Casting of Specimen

3 Results and Discussion

Hybrid fibers improved the concrete mechanical properties made with recycled aggregates significantly such that increased RCA would not override its advantages. The concrete is as per IS 516:1959.

3.1 Compressive Strength

Compressive strength test results indicate that strength decreases as RCA replacement levels increase. The inclusion of hybrid fibres would greatly improve strength through bridging micro-cracks and improving stress redistribution. 30% RCA and 1% hybrid fibre mix met the criteria of M25 grade concrete with a compressive strength of 27.4 MPa at 28 days as shown in Table 2.

Table 2. Compressive Strength Results (MPa)

Mix ID	RCA (%)	7 days	14 days	28 days	7 days (1% fibre)	14 days (1% fibre)	28 days (1% fibre)
Control (M0)	0	18.2	22.5	28.4	19.6	24.1	30.2
M1	10	17.8	22.1	27.8	19.2	23.8	29.6
M2	20	17.2	21.4	26.9	18.7	23.2	28.7
M3	30	16.5	20.6	25.8	18.1	22.5	27.4
M4	40	15.7	19.4	24.3	17.2	21.3	25.8
M5	50	14.8	18.2	22.7	16.1	20.1	24.1

This indicates that the 30% RCA is in the range of strength and environmental sustainability; that is, resistance to cracking and fracture compared to surface hardness. Fibers are particularly useful in this situation because they can bridge cracks and redistribute load on your structure, allowing it to deform for a longer period of time before failing. Compressive strength shown in Fig 4.

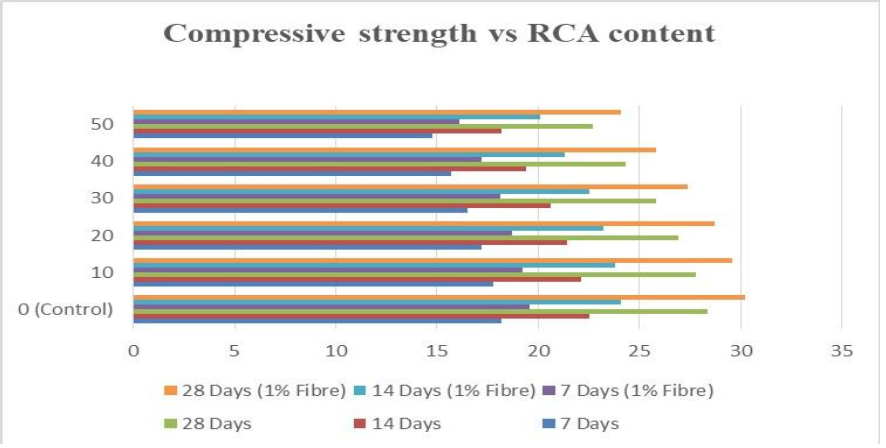

Fig. 4. Compressive strength vs RCA content

3.2 Split Tensile Strength

The split tensile strength increased progressively with the increase in hybrid fibres at all RCA level of replacements as Table 3. The maximum enhancement was observed for mixes containing 1% hybrid fibre content and then beyond that slight reduction was noted owing to clustering of fibres as shown in Fig 5 according to IS 5816:1999.

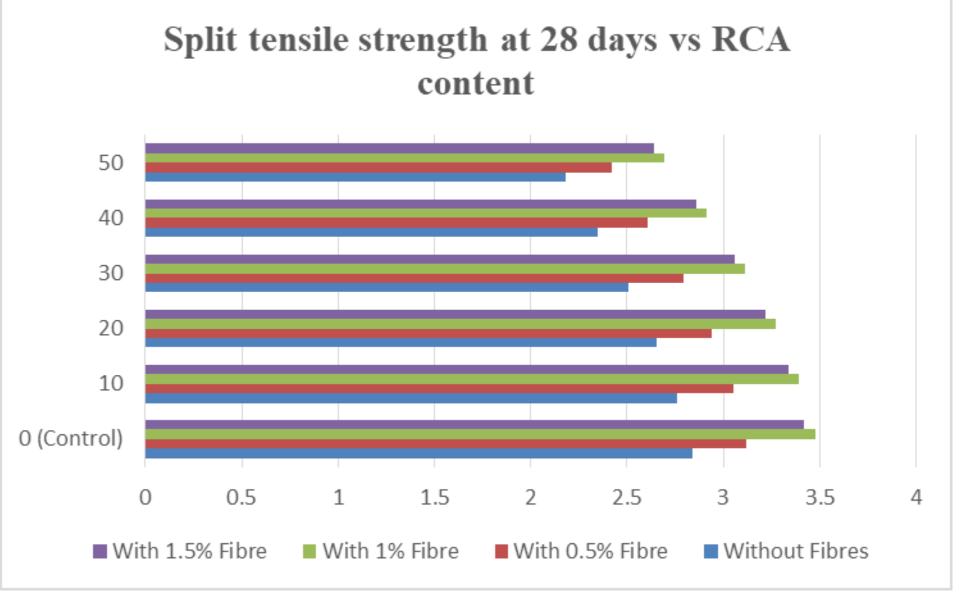

Fig. 5. Split tensile strength at 28 days vs RCA content

Table 3. Split Tensile Strength Results at 28 Days (MPa)

Mix ID	RCA (%)	Without fibres	With 0.5% fibre	With 1% fibre	With 1.5% fibre
Control (M0)	0	2.84	3.12	3.48	3.42

M1	10	2.76	3.05	3.39	3.34
M2	20	2.65	2.94	3.27	3.22
M3	30	2.51	2.79	3.11	3.06
M4	40	2.35	2.61	2.91	2.86
M5	50	2.18	2.42	2.69	2.64

3.3 Flexural Strength

Flexural strength results as given in Fig 6, demonstrated enhanced ductility and post-cracking behaviour for fibre-reinforced mixes. The synergistic action of polypropylene and nylon fibres improved energy absorption capacity, particularly for mixes with RCA replacement up to 30% as shown in Table 4.

Table 4. Flexural Strength Results at 28 Days (MPa)

Mix ID	RCA (%)	Without fibre	With 0.5% fibre	With 1% fibre	With 1.5% fibre
Control (M0)	0	4.52	5.18	5.76	5.68
M1	10	4.41	5.04	5.61	5.54
M2	20	4.26	4.87	5.42	5.35
M3	30	4.08	4.66	5.19	5.12
M4	40	3.84	4.39	4.89	4.82
M5	50	3.57	4.08	4.54	4.48

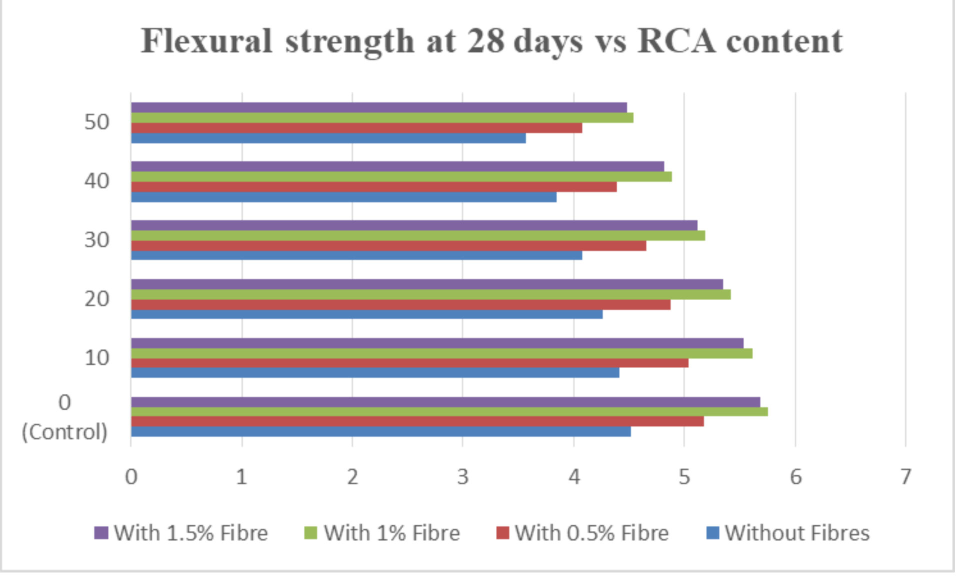

Fig. 6. Flexural strength at 28 days vs RCA content

3.4 Discussion

Results revealed that the optimum mix design with a combination of 30% RCA replacement and 1% hybrid fibre content (0.5 polypropylene + 0.5 nylon) could provide both structural reliability and enhance mechanical performance:

- ✓ The compressive strength after 28 days is 27.4 MPa, surpassing the M25 requirement of 25 MPa.
- ✓ Approximately 24% improvement in split tensile strength compared to plain RAC
- ✓ The RAC exhibits a 27% improvement in flexural strength compared to its plain counterpart.
- ✓ Characteristics that provide increased durability, making them suitable for long-term structural applications.

Polypropylene with nylon is one illustration: a 50:50 mixture yields two good things — polypropylene to mitigate cracks and plastic shrinkage, along with nylon for higher post-crack tensile strength and enhanced overall toughness. However, in the case when RCA substitute over 30% natural aggregate, even the optimized fiber distribution cannot hold off strength to go below M25 grade minimum. RCA's deficiencies of higher porosity, mortar retention and water absorption.

4 Conclusion

The experimental investigation demonstrated that the combined use of recycled coarse aggregate and hybrid fibre reinforcement can produce sustainable concrete with satisfactory structural performance. The optimum mix consisted of 30% RCA replacement and 1% hybrid fibre content, which achieved a 28-day compressive strength greater than 25 MPa along with improved tensile, flexural, and durability characteristics. The study confirms that hybrid fibre-reinforced recycled aggregate concrete is a viable and sustainable alternative to conventional concrete for structural applications.

Conflicts of Interest

The authors do not have any conflicts of interest to disclose.

Data Availability

The information produced and processed in the present research is not publicly accessible because of the institutional limitations and the ongoing research on the topic. However, the datasets used in this study can be obtained from the corresponding author upon reasonable request

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