

Experimental Study on Behaviour of Steel Fibre Reinforced Recycled Aggregate Concrete

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ABSTRACT

The rapid growth of construction activity has increased the demand for natural aggregates while generating large quantities of construction and demolition (C&D) waste. Recycled Aggregate Concrete (RAC), produced by replacing natural coarse aggregate with aggregate recovered from demolished concrete, offers a sustainable alternative that conserves natural resources and reduces landfill burden. However, the adhered mortar, higher porosity, higher water absorption, and weaker interfacial transition zones of recycled aggregate reduce the strength and durability of the resulting concrete. The incorporation of steel fibres, which bridge cracks and improve tensile and post-cracking behaviour, offers an effective means of offsetting these deficiencies.

The present study investigates the fresh, mechanical, non-destructive, and durability-related behaviour of M40 grade Steel Fibre Reinforced Recycled Aggregate Concrete (SFRRAC) through a full factorial experimental programme. Natural coarse aggregate was replaced with recycled coarse aggregate at four levels (0%, 25%, 50%, and 100%), and hooked-end steel fibres were added at four dosages (0%, 0.5%, 1.0%, and 1.5% by volume), giving sixteen distinct mixes. The base mix was designed for M40 grade at a water–cement ratio of 0.40 in accordance with IS 10262:2019. Workability was assessed by the slump test; compressive, split tensile, and flexural strengths were determined at 7 and 28 days; water absorption was measured as a durability index; and surface hardness was evaluated using the Rebound Hammer test. All reported strengths are the mean of three specimens.

The results show that increasing recycled aggregate content systematically reduced workability, compressive, split tensile, and flexural strengths, and increased water absorption, owing to the inferior quality of the recycled aggregate. Conversely, steel fibre addition improved all mechanical properties up to a dosage of 1.0%, beyond which a marginal reduction occurred due to fibre balling and reduced compaction; workability declined continuously with fibre content. At the 1.0% fibre dosage, which gave the highest mean strength at every replacement level, the compressive strength of the 25% recycled mix (45.3 MPa) slightly exceeded that of the plain natural-aggregate control (43.8 MPa), while the 50% recycled mix (42.3 MPa) recovered to within 3.4% of it, demonstrating that steel fibres can largely compensate for the strength loss caused by recycled aggregate up to a replacement level of about 50%. It is concluded that M40 grade recycled aggregate concrete containing 1.0% steel fibre and up to 50% recycled aggregate provides a sustainable concrete of satisfactory mechanical performance suitable for a range of construction applications.

Keywords: Recycled Aggregate Concrete; Steel Fibre Reinforced Recycled Aggregate Concrete; M40 Grade; Construction and Demolition Waste; Sustainable Concrete; Compressive Strength; Split Tensile Strength; Flexural Strength; Water Absorption; Rebound Hammer Test.

CHAPTER 1

INTRODUCTION

1.1 Background and Motivation

Concrete is the most widely used construction material in the world and forms the backbone of modern infrastructure. It is used extensively in buildings, bridges, highways, dams, tunnels, airports, and industrial structures on account of its high compressive strength, durability, versatility, and cost-effectiveness. In conventional concrete, aggregates occupy nearly 60–75% of the total volume; consequently, the quality and availability of aggregates strongly influence both the performance and the sustainability of concrete construction.

Rapid urbanisation and industrialisation have produced an unprecedented demand for natural construction materials, particularly coarse and fine aggregates. The large-scale extraction of natural aggregates from quarries and riverbeds has led to the depletion of natural resources, ecological imbalance, and rising material costs. At the same time, the construction industry generates enormous quantities of construction and demolition (C&D) waste through the renovation, reconstruction, and demolition of ageing structures. Concrete debris constitutes a major fraction of this waste, and its disposal in landfills occupies valuable land and contributes to environmental pollution. The twin problems of resource depletion and waste disposal have therefore become central concerns of sustainable construction.

One of the most promising approaches to addressing both problems simultaneously is the use of recycled aggregates in concrete. Recycled coarse aggregates are produced by crushing and processing waste concrete obtained from demolished structures, and can partially or completely replace natural coarse aggregates. Their use reduces the demand for virgin materials, diverts waste from landfill, and supports the principles of the circular economy. However, recycled aggregates generally carry remnants of old cement mortar adhered to their surfaces, which increases porosity and water absorption while reducing density and strength. As a result, Recycled Aggregate Concrete (RAC) typically exhibits lower compressive strength, reduced modulus of elasticity, increased shrinkage, and decreased durability compared with concrete made from natural aggregates, particularly at high replacement levels. These limitations have restricted the widespread structural adoption of RAC.

To overcome these deficiencies, researchers have investigated pre-treatment of aggregates, the use of mineral and chemical admixtures, and fibre reinforcement. Among these, fibre reinforcement has proved especially effective. Steel fibres are discrete reinforcing elements distributed randomly throughout the concrete matrix; they act as crack arresters, bridging micro-cracks that form under load and restricting their propagation. In doing so, they enhance tensile strength, flexural strength, impact and fatigue resistance, toughness, and post-cracking behaviour. Unlike conventional bar reinforcement, which is placed only at specific locations, steel fibres provide three-dimensional reinforcement throughout the concrete mass, significantly improving its ductility and energy-absorption capacity. Hooked-end steel fibres are the most widely used because their deformed ends develop mechanical anchorage that delays fibre pull-out.

The combination of recycled aggregates and steel fibres has attracted considerable attention in recent years. While recycled aggregates contribute to environmental sustainability, steel fibres compensate for the associated loss of mechanical performance. The resulting material, Steel Fibre Reinforced Recycled Aggregate Concrete (SFRRAC), offers the potential to achieve both sustainability and structural performance, and is suited to pavements, industrial floors, retaining structures, precast elements, and low- to medium-rise construction where enhanced crack resistance and durability are required. In the present study, M40 grade concrete has been selected because it represents a common structural grade for medium- to high-strength applications. Recycled

aggregates are used as partial and full replacements for natural coarse aggregate, and steel fibres are incorporated across a range of dosages, in order to evaluate their combined influence and to establish the optimum fibre content.

1.2 Problem Statement

The construction industry faces two pressing challenges: the depletion of natural aggregate resources and the increasing generation of construction and demolition waste. The continuous extraction of natural aggregates causes environmental degradation and resource scarcity, while the disposal of demolished concrete in landfills creates waste-management concerns. The use of recycled aggregates offers a sustainable alternative, but recycled aggregate concrete generally exhibits lower mechanical properties and durability owing to the adhered mortar, higher porosity, and higher water absorption of the recycled aggregate.

Steel fibres can potentially offset these deficiencies by improving crack resistance, tensile strength, flexural strength, and ductility. However, their addition also reduces workability, and the extent to which fibres can compensate for the strength loss at different recycled-aggregate replacement levels is not well established for M40 grade concrete. In particular, the optimum steel fibre dosage that maximises mechanical performance without unacceptably impairing workability, and the highest recycled-aggregate replacement level that remains structurally acceptable, require systematic experimental investigation. The present study addresses these questions through a full factorial programme covering four replacement levels and four fibre dosages.

1.3 Objectives of the Project

The specific objectives of the present investigation are as follows:

1. To design an M40 grade concrete using recycled coarse aggregate as a replacement for natural coarse aggregate at levels of 0%, 25%, 50%, and 100%, in accordance with IS 10262:2019.
2. To study the combined effect of recycled aggregate replacement and steel fibre dosage (0%, 0.5%, 1.0%, and 1.5% by volume) on the workability of fresh concrete.
3. To determine the compressive strength of the concrete mixes at 7 and 28 days of curing.
4. To evaluate the split tensile and flexural strengths of the mixes at 7 and 28 days.
5. To assess the durability of the concrete through the water absorption test, and its surface hardness and uniformity through the Rebound Hammer test.
6. To identify the optimum steel fibre dosage and the extent to which steel fibres compensate for the strength loss caused by recycled aggregate, and hence the maximum viable replacement level for structural use.

1.4 Scope of the Project

The present study is limited to a laboratory investigation of M40 grade Steel Fibre Reinforced Recycled Aggregate Concrete produced with locally available materials. Recycled coarse aggregate obtained from processed demolition waste is used at replacement levels of 0%, 25%, 50%, and 100%, and hooked-end steel fibres are incorporated at 0%, 0.5%, 1.0%, and 1.5% by volume, giving a full factorial matrix of sixteen mixes. The programme comprises material characterisation, mix design, casting and curing of specimens, and testing of fresh, hardened, non-destructive, and durability-related properties.

Fresh concrete is evaluated by the slump test; mechanical properties are assessed through compressive, split tensile, and flexural strength tests at 7 and 28 days; durability is indicated by water absorption; and surface hardness is examined through the Rebound Hammer test. The study does not include chloride penetration, sulphate attack, carbonation, freeze–thaw resistance, long-term durability, fatigue behaviour, or full-scale structural testing, nor does it address economic or life-cycle analysis. All conclusions are

drawn from controlled laboratory experiments conducted under standard curing conditions, and all reported strengths are the mean of three specimens.

1.5 Organization of the Report

The remainder of this report is organised into four chapters, as summarised below:

- **Chapter 2** reviews the published literature on recycled aggregate concrete, steel fibre reinforced concrete, and their combination, and identifies the research gap addressed in this work.
- **Chapter 3** describes the materials and their properties, the mix design, the experimental matrix, specimen preparation, curing, and the testing methodology for the fresh, hardened, non-destructive, and durability tests.
- **Chapter 4** presents and discusses the experimental results, supported by tables and graphs, interprets the observed behaviour in terms of material mechanisms, and compares the findings with the literature.
- **Chapter 5** summarises the principal conclusions and outlines directions for future research.

CHAPTER 2

LITERATURE REVIEW

2.1 General

The behaviour of recycled aggregate concrete and steel fibre reinforced concrete has been the subject of extensive research over the past two decades. Recycled aggregate concrete has been studied primarily for its environmental benefits and for the technical challenges arising from the inferior quality of recycled aggregate, while steel fibre reinforced concrete has been investigated for its enhanced tensile, flexural, and post-cracking performance. More recently, attention has turned to the combination of the two, in which steel fibres are used to offset the mechanical deficiencies of recycled aggregate concrete. This chapter reviews the relevant literature on these three themes and identifies the research gap addressed in the present study.

2.2 Recycled Aggregate Concrete

Recycled aggregate concrete is produced by replacing part or all of the natural coarse aggregate with aggregate recovered from crushed demolition waste. The distinguishing feature of recycled aggregate is the layer of old cement mortar adhered to the surface of the original aggregate. This adhered mortar is porous and micro-cracked, and it raises the water absorption and lowers the density and strength of the aggregate relative to natural stone. It also introduces an additional, weaker interfacial transition zone (ITZ) between the old and new mortar. Consequently, recycled aggregate concrete generally shows reduced compressive strength, lower stiffness, higher shrinkage, and greater permeability, with the reductions becoming more pronounced as the replacement level increases. The literature broadly agrees that replacement levels up to about 50% can be used with only moderate loss of performance, whereas full replacement leads to more significant reductions unless compensating measures are adopted.

2.3 Steel Fibre Reinforced Concrete

Steel fibre reinforced concrete is a composite in which discrete steel fibres are distributed throughout the matrix. Concrete is strong in compression but weak in tension; under tensile stress, micro-cracks nucleate and propagate until failure. Steel fibres bridge these cracks, transferring stress across the crack faces and delaying propagation, thereby markedly improving tensile strength, flexural strength, toughness, ductility, and impact and fatigue resistance. The effectiveness of the fibres depends on their geometry, aspect ratio, volume fraction, and dispersion; hooked-end fibres are the most widely used because their anchored ends develop superior pull-out resistance. In the context of recycled aggregate concrete, steel fibres are of particular interest because their crack-bridging action can counteract the increased crack-sensitivity introduced by the weaker recycled aggregate and its interfacial zones.

2.4 Review of Previous Studies

The most relevant experimental and review studies are summarised below.

Zhang et al. (2023) investigated the effects of steel fibre content, strain rate, and recycled aggregate replacement ratio on the splitting tensile behaviour of SFRRAC using a Split Hopkinson Pressure Bar and examined the microstructure by scanning electron microscopy. Recycled aggregate reduced the static splitting tensile strength, whereas steel fibres significantly improved tensile performance, with an optimum fibre content of about 1.0–1.5%. At 50% replacement, concrete with 1.0% fibre showed tensile strength comparable to conventional concrete, and the fibres were found to improve the interfacial transition zone.

Kou and Poon (2015) studied the engineering properties of recycled aggregate concrete produced from C&D waste and showed that recycled aggregate could successfully replace natural aggregate in structural concrete when appropriate mix-design procedures were adopted, although increasing recycled-aggregate content reduced compressive strength and modulus of elasticity owing to higher water absorption and weaker bonding.

Silva, de Brito and Dhir (2014) reviewed the properties of recycled aggregate concrete and reported that the physical characteristics of the recycled aggregate strongly govern concrete performance, concluding that replacement levels up to 50% could be adopted without substantial loss of mechanical properties when suitable quality control was applied.

Guo et al. (2018) examined the mechanical behaviour of steel fibre reinforced recycled aggregate concrete under compression and flexure and found that steel fibres significantly improved ductility, energy absorption, and crack resistance, and partially compensated for the strength losses associated with recycled aggregate replacement.

Afroughsabet and Ozbakkaloglu (2015) studied the influence of steel fibres on high-strength concrete and reported substantial improvements in tensile and flexural strength and reduced crack widths, recommending fibre contents in the range 0.5–1.5% for optimum mechanical performance.

Yoo and Banthia (2016) reviewed the mechanical and durability characteristics of steel fibre reinforced concrete and confirmed that hooked-end steel fibres provide superior crack-bridging capability and enhance load-carrying capacity under both static and dynamic loading, with fibre geometry, aspect ratio, and dosage being the decisive parameters.

Ali and Qureshi (2019) investigated the flexural performance of steel fibre reinforced recycled aggregate concrete beams and reported that the fibres enhanced load-carrying capacity, delayed crack propagation, and improved overall structural behaviour, effectively compensating for the reduced strength of the recycled aggregate.

Xiao, Li and Zhang (2005) studied the mechanical properties of recycled aggregate concrete at varying replacement levels and found that compressive strength and elastic modulus decreased with increasing recycled-aggregate content, but that concrete containing up to 50% recycled aggregate retained acceptable structural performance.

Thomas et al. (2018) evaluated the durability of recycled aggregate concrete and reported that water absorption and permeability increased with recycled-aggregate content, while the use of supplementary cementitious materials and fibre reinforcement improved durability and reduced these adverse effects.

Soutsos, Le and Lampropoulos (2012) studied the combined effect of recycled aggregates and steel fibres and concluded that steel fibres compensated for the strength reductions caused by recycled-aggregate replacement and significantly improved tensile and flexural performance, indicating considerable potential for sustainable structural applications.

2.5 Research Gap

The reviewed literature establishes that recycled aggregate reduces the strength and durability of concrete, that steel fibres improve its tensile, flexural, and post-cracking behaviour, and that fibres can partially compensate for the deficiencies of recycled aggregate. Nevertheless, reported results vary widely owing to differences in aggregate quality, fibre geometry, fibre dosage, and mix proportions, and the individual effects of the two variables have more often been studied separately than in combination.

In particular, relatively few investigations have systematically examined M40 grade concrete over the full range of recycled-aggregate replacement (from 0% to 100%) in combination with several steel fibre dosages within a single, consistent programme. As a result, the optimum fibre content for this grade, and the degree to which fibres can restore the performance lost through recycled-aggregate replacement, remain uncertain. The present study addresses this gap through a full 4×4 factorial programme that evaluates the workability, compressive, split tensile, and flexural strengths, water absorption, and non-destructive characteristics of M40 grade SFRRAC, and thereby identifies both the optimum fibre dosage and the maximum viable replacement level for structural use.

2.6 Summary of Literature Review

The literature reviewed in this chapter demonstrates that recycled aggregate concrete is an environmentally attractive material whose mechanical performance and durability are nonetheless diminished by the adhered mortar and weaker interfacial zones of the recycled aggregate, with the reductions increasing at higher replacement levels. It further establishes that steel fibres substantially improve tensile strength, flexural strength, toughness, and crack resistance, and that their crack-bridging action can offset much of the strength loss associated with recycled aggregate.

The combined use of recycled aggregates and steel fibres therefore offers a route to concrete that is both sustainable and structurally satisfactory, provided the fibre dosage and replacement level are appropriately chosen. On this basis, the present study has been undertaken to evaluate the performance of M40 grade SFRRAC across the full range of replacement levels and fibre dosages, and to determine the optimum combination for practical structural application.

CHAPTER 3

MATERIALS AND METHODOLOGY

3.1 Materials Used

The materials used in the preparation of the concrete mixes comprised Portland Slag Cement (PSC), natural river sand as fine aggregate, crushed stone as natural coarse aggregate, processed recycled coarse aggregate, hooked-end steel fibres, potable water, and a polycarboxylate-ether-based superplasticiser. All materials were selected and tested in accordance with the relevant Indian Standard specifications to ensure the consistency and reliability of the experimental results. The physical properties of each constituent were determined before use, since they govern the workability, strength, and durability of the resulting concrete and serve as inputs to the mix design presented in Appendix A.

3.2 Physical Properties of Materials

3.2.1 Cement

Portland Slag Cement conforming to IS 455:2015 was used as the binder throughout the investigation. PSC was selected for its improved durability, lower heat of hydration, enhanced resistance to aggressive environments, and its contribution to sustainable construction through the utilisation of granulated blast-furnace slag. The physical properties of the cement, determined through standard laboratory tests, are summarised in Table 3.1.

Table 3.1: Physical Properties of Cement

Property	Value	Requirement (IS 455:2015)
Type of Cement	Portland Slag Cement (PSC)	—
Specific Gravity	2.90	—
Standard Consistency	36%	—
Initial Setting Time	120 min	> 30 min
Final Setting Time	240 min	< 600 min
Soundness (Le-Chatelier)	2 mm	≤ 10 mm

The measured properties satisfy the requirements of IS 455:2015. The initial and final setting times fall within the prescribed limits, and the soundness value of 2 mm confirms volumetric stability. The cement was therefore found suitable for the production of the concrete mixes.

3.2.2 Fine Aggregate

Locally available natural river sand conforming to Zone II grading as per IS 383:2016 was used as fine aggregate. Fine aggregate improves the cohesiveness and workability of concrete and reduces voids within the matrix. The physical properties of the fine aggregate are summarised in Table 3.2.

Table 3.2: Physical Properties of Fine Aggregate

Property	Value
Type	Natural River Sand
Grading Zone (IS 383:2016)	Zone II
Specific Gravity	2.60

Property	Value
Fineness Modulus	2.65
Water Absorption	1.75%
Moisture Content	1.01%

A specific gravity of 2.60 and a fineness modulus of 2.65 place the sand within Zone II, and the low water absorption confirms its suitability for producing workable, cohesive concrete.

3.2.3 Natural Coarse Aggregate

Crushed angular stone aggregate of 20 mm nominal maximum size was used as natural coarse aggregate. Coarse aggregate forms the load-bearing skeleton of concrete and governs its strength and stiffness. The aggregate was tested in accordance with IS 2386, and its properties are summarised in Table 3.3.

Table 3.3: Physical Properties of Natural Coarse Aggregate

Property	Value
Nominal Maximum Size	20 mm
Type	Crushed Angular
Specific Gravity	2.80
Water Absorption	2.02%
Moisture Content	1.29%
Aggregate Impact Value	9.80%
Aggregate Crushing Value	18.50%

The low impact and crushing values, both well below the 30% limit for structural aggregate, together with a specific gravity of 2.80 and low water absorption, confirm that the natural coarse aggregate possesses adequate strength and durability.

3.2.4 Recycled Coarse Aggregate

Recycled coarse aggregate was obtained by crushing, cleaning, and grading concrete recovered from construction and demolition waste, and was used at a nominal maximum size of 20 mm to match the natural aggregate. Its properties are compared with those of the natural aggregate in Table 3.4.

Table 3.4: Physical Properties of Recycled Coarse Aggregate

Property	Recycled Aggregate	Natural Aggregate
Nominal Maximum Size	20 mm	20 mm
Specific Gravity	2.50	2.80
Water Absorption	5.20%	2.02%
Moisture Content	2.10%	1.29%
Aggregate Impact Value	22.00%	9.80%
Aggregate Crushing Value	26.00%	18.50%

The recycled aggregate has a markedly lower specific gravity (2.50 versus 2.80) and a much higher water absorption (5.20% versus 2.02%) than the natural aggregate, together with higher impact and crushing values. These differences arise from the porous, micro-cracked layer of old mortar adhered to the recycled aggregate, and they are directly responsible for the reduced strength and increased

water absorption of the recycled aggregate concrete reported in Chapter 4. To limit the loss of workability associated with the high absorption, the recycled aggregate was used in a pre-soaked, saturated surface-dry condition.

3.2.5 Steel Fibres

Hooked-end steel fibres were used as discrete reinforcement. Their deformed ends provide mechanical anchorage within the matrix, delaying pull-out and enhancing crack-bridging efficiency, toughness, and post-cracking behaviour. The properties of the steel fibres are given in Table 3.5.

Table 3.5: Properties of Steel Fibres

Property	Value
Type	Hooked-End Steel Fibre
Length (l)	30 mm
Diameter (d)	0.50 mm
Aspect Ratio (l/d)	60
Tensile Strength	1100 MPa
Density	7850 kg/m ³

The selected fibres, with an aspect ratio of 60, offer a favourable balance between crack-bridging efficiency and uniform dispersion in the fresh mix, and were adopted for all fibre-reinforced mixes.

3.2.6 Superplasticiser

A polycarboxylate-ether-based high-range water-reducing admixture was used to achieve the required workability without increasing the water–cement ratio, which is particularly important for the recycled-aggregate mixes on account of their higher water demand. Its properties are listed in Table 3.6.

Table 3.6: Properties of Superplasticiser

Property	Value
Type	Polycarboxylate Ether Based
Appearance	Brown Liquid
Specific Gravity	1.08
Recommended Dosage	0.5–2.0% by weight of cement
Chloride Content	Nil

A dosage of 1.0% by weight of cement was adopted on the basis of trial mixes, as discussed in Section 3.3.

3.3 Mix Design

The concrete was designed for M40 grade in accordance with IS 10262:2019 and IS 456:2000. The target mean compressive strength is given by Equation (3.1):

$$f'_{ck} = f_{ck} + 1.65 S \quad (3.1)$$

where f'_{ck} is the target mean compressive strength at 28 days, f_{ck} is the characteristic strength (40 MPa for M40), and S is the assumed standard deviation (5 MPa for M40 as per IS 10262:2019). Substituting these values gives $f'_{ck} = 40 + 1.65 \times 5 = 48.25$ MPa, which is adopted as the target mean strength.

A water–cement ratio of 0.40 was selected, which lies within the limit prescribed for durable structural concrete. The mix was proportioned to a cement content of 380 kg/m³ with a corresponding water content of 152 kg/m³, and the superplasticiser was dosed at 1.0% by weight of cement (3.80 kg/m³). The fine and coarse aggregate contents were established as 684 kg/m³ and 1277 kg/m³ respectively, giving a nominal mix ratio of 1 : 1.80 : 3.36 (cement : fine aggregate : coarse aggregate). The detailed mix-design calculations are presented in Appendix A.

The same base mix was used for all sixteen mixes. Natural coarse aggregate was replaced by recycled coarse aggregate on a one-to-one mass basis at 0%, 25%, 50%, and 100%, and hooked-end steel fibres were added at 0%, 0.5%, 1.0%, and 1.5% by volume of concrete. The corresponding fibre mass was obtained by multiplying the volume fraction by the fibre density of 7850 kg/m³, giving 39.25, 78.50, and 117.75 kg/m³ for the 0.5%, 1.0%, and 1.5% dosages respectively.

It should be noted that, because the recycled aggregate has a lower specific gravity (2.50) than the natural aggregate (2.80), replacement on a mass basis produces a small increase in the absolute volume of the coarse aggregate, and hence in the batch yield, of the recycled-aggregate mixes — of the order of 2%, 3%, and 6% at 25%, 50%, and 100% replacement respectively. This minor yield variation, which slightly dilutes the paste at high replacement levels, is a recognised consequence of mass-basis replacement and is noted here as a limitation of the adopted procedure.

3.3.1 Experimental Matrix

The full factorial experimental matrix, comprising four replacement levels and four fibre dosages, is presented in Table 3.7. Each mix is identified by its recycled-aggregate level (NC for natural control, or RAC-25/50/100) and its steel fibre dosage (SF0 to SF1.5).

Table 3.7: Experimental Matrix

Mix ID	RA Replacement (%)	Steel Fibre (%)	Fibre Mass (kg/m ³)
NC-SF0	0	0.0	0.00
NC-SF0.5	0	0.5	39.25
NC-SF1.0	0	1.0	78.50
NC-SF1.5	0	1.5	117.75
RAC25-SF0 – SF1.5	25	0.0 – 1.5	0.00 – 117.75
RAC50-SF0 – SF1.5	50	0.0 – 1.5	0.00 – 117.75
RAC100-SF0 – SF1.5	100	0.0 – 1.5	0.00 – 117.75

For each recycled-aggregate level, the four fibre dosages were applied in the same manner as shown explicitly for the natural-control series, giving sixteen distinct mixes in total. This factorial arrangement enables the independent and combined effects of recycled-aggregate replacement and fibre dosage to be evaluated systematically.

3.3.2 Mix Proportion

The proportions of the base mix, common to all sixteen combinations, are presented in Table 3.8. For the recycled-aggregate mixes, the stated coarse-aggregate quantity is made up of natural and recycled aggregate in the proportions defined by the replacement level.

Table 3.8: Mix Proportion of the Base M40 Concrete

Material	Quantity (kg/m ³)
Cement (PSC)	380
Water	152
Fine Aggregate	684
Coarse Aggregate (natural + recycled)	1277
Superplasticiser	3.80
Water–Cement Ratio	0.40

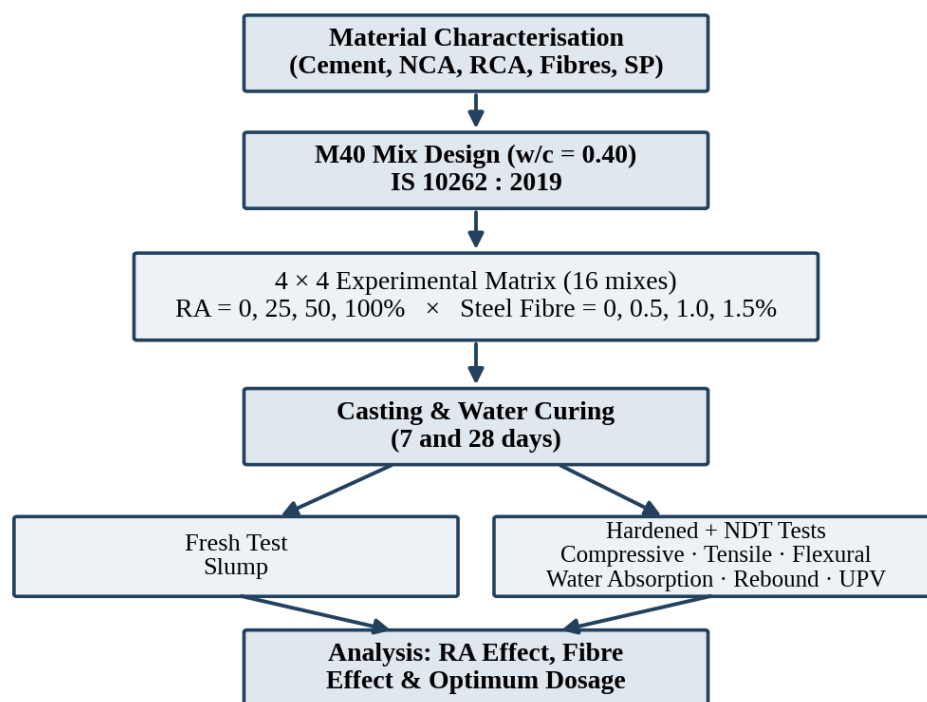


Figure 3.1: Flowchart of the experimental programme

Figure 3.1 illustrates the overall experimental programme. Following material characterisation and mix design, the sixteen mixes of the 4 × 4 matrix were cast and cured, after which the fresh, hardened, non-destructive, and durability tests were performed and the results analysed to establish the effects of recycled-aggregate replacement and fibre dosage and to identify the optimum combination.

3.4 Specimen Preparation

All specimens were prepared under controlled laboratory conditions with accurate batching by weight. Cement, fine aggregate, natural coarse aggregate, and (where applicable) recycled coarse aggregate were first dry-mixed until uniform. For the fibre-reinforced mixes, the steel fibres were then added gradually to the dry mix to ensure uniform dispersion and to prevent fibre balling. Water containing the pre-dissolved superplasticiser was subsequently added, and mixing continued until a homogeneous, workable mix was obtained. The fresh concrete was placed in standard steel moulds and compacted on a vibrating table, and the exposed surfaces were finished with a trowel. The types and dimensions of the specimens are listed in Table 3.9.

Table 3.9: Details of Test Specimens

Specimen Type	Dimensions	Test
Cube	150 mm × 150 mm × 150 mm	Compressive strength, rebound, water absorption
Cylinder	150 mm dia. × 300 mm height	Split tensile strength
Beam (Prism)	500 mm × 100 mm × 100 mm	Flexural strength

Three specimens were cast for each mix, test, and curing age so that representative average values could be obtained, giving a total of ninety-six cubes, ninety-six cylinders, and ninety-six beams across the sixteen mixes. Each specimen was labelled according to its mix designation and testing age to facilitate systematic testing and data recording.

3.5 Curing Procedure

After casting, the specimens were left undisturbed in the laboratory for approximately 24 hours, then demoulded and transferred to a curing tank of clean potable water. Continuous water curing was adopted to ensure adequate hydration and uniform strength development. The specimens were cured until the designated testing ages of 7 and 28 days, with the water level monitored to maintain full immersion. On completion of curing, the specimens were removed, cleaned, and brought to a surface-dry condition before testing.

3.6 Testing Methodology

The performance of the mixes was evaluated through tests on fresh and hardened concrete, supplemented by non-destructive and durability testing. The methods adopted for each property are described below.

3.6.1 Workability Test

The workability of the fresh concrete was assessed by the slump test in accordance with IS 1199. The concrete was placed in a standard slump cone in three layers, each tamped, and the cone was lifted vertically; the vertical settlement of the concrete, measured in millimetres, was recorded as the slump. The slump test provides a simple and reliable index of the consistency and workability of the mix and was used to compare the sixteen combinations.

3.6.2 Compressive Strength Test

Compressive strength was determined on 150 mm cubes in a compression testing machine in accordance with IS 516, at 7 and 28 days. The compressive strength is given by Equation (3.2):

$$f_c = P / A \quad (3.2)$$

where f_c is the compressive strength (MPa), P is the failure load (N), and A is the loaded cross-sectional area of the cube (22 500 mm²). The reported values are the average of three specimens.

3.6.3 Split Tensile Strength Test

Split tensile strength was determined on 150 mm × 300 mm cylinders in accordance with IS 5816, at 7 and 28 days. A cylinder was loaded in compression along its length, inducing tensile stress across the vertical diametral plane and causing it to split. The split tensile strength is given by Equation (3.3):

$$f_{ct} = 2P / (\pi L D) \quad (3.3)$$

where f_{ct} is the split tensile strength (MPa), P is the failure load (N), L is the length of the cylinder (300 mm), and D is its diameter (150 mm).

3.6.4 Flexural Strength Test

Flexural strength was determined on 500 mm × 100 mm × 100 mm prisms under two-point loading in accordance with IS 516, at 7 and 28 days. The flexural strength, or modulus of rupture, is given by Equation (3.4):

$$f_b = P L / (b d^2) \quad (3.4)$$

where f_b is the flexural strength (MPa), P is the failure load (N), L is the effective span (400 mm), and b and d are the width and depth of the prism (each 100 mm).

3.6.5 Water Absorption Test

Water absorption was measured as a durability index in accordance with IS 1124. Oven-dried cubes were weighed, immersed in water for the prescribed period, and re-weighed in the saturated surface-dry condition. The water absorption is given by Equation (3.5):

$$WA (\%) = [(W_2 - W_1) / W_1] \times 100 \quad (3.5)$$

where W_1 is the oven-dried mass and W_2 is the saturated surface-dry mass of the specimen. A higher water absorption indicates greater porosity and lower durability.

3.6.6 Rebound Hammer Test

The Rebound Hammer test was performed on the 28-day cubes as a non-destructive assessment of surface hardness and an indirect indicator of compressive strength, in accordance with IS 13311 (Part 2). A spring-loaded mass was released against the prepared surface of the cube, and the rebound of the mass, expressed as the rebound number, was recorded. Several readings were taken over each surface and averaged, a higher rebound number indicating harder and stronger concrete. The test was carried out while the cube was held under a compression testing machine to provide the required reaction, before the same cube was loaded to failure for the compressive strength test. The rebound results are presented and interpreted in Chapter 4.

3.6.7 Data Analysis

The results of all tests were tabulated and analysed comparatively across the four replacement levels and four fibre dosages. The influence of each variable on workability, compressive, split tensile, and flexural strength, water absorption, and rebound number was examined graphically, and the percentage change relative to the appropriate reference was computed. In addition, the inter-relationships between the mechanical properties were quantified through correlation and regression analysis, and the relative contributions of the two variables were examined through a variance decomposition, as presented in Section 4.8. The observed trends were interpreted in terms of established material mechanisms and compared with the literature to determine the optimum fibre dosage and the maximum viable replacement level, as presented in Chapter 4.

CHAPTER 4

RESULTS AND DISCUSSION

This chapter presents and discusses the experimental results for the sixteen mixes of the 4×4 factorial programme. The workability results are considered first, followed by the compressive, split tensile, and flexural strengths, the non-destructive test results, and the water absorption. A comparative assessment then quantifies the effect of recycled-aggregate replacement, the effect of steel fibre dosage, and the extent to which fibres compensate for the recycled-aggregate strength loss, leading to the identification of the optimum combination. Throughout, the observed behaviour is interpreted in terms of the underlying material mechanisms and compared with the literature.

4.1 Workability (Slump)

The slump values of all sixteen mixes are presented in Table 4.1 and illustrated in Figure 4.1.

Table 4.1: Slump Test Results

Mix ID	RA (%)	Steel Fibre (%)	Slump (mm)
NC-SF0	0	0.0	110
NC-SF0.5	0	0.5	92
NC-SF1.0	0	1.0	74
NC-SF1.5	0	1.5	58
RAC25-SF0	25	0.0	102
RAC25-SF0.5	25	0.5	85
RAC25-SF1.0	25	1.0	65
RAC25-SF1.5	25	1.5	52
RAC50-SF0	50	0.0	95
RAC50-SF0.5	50	0.5	76
RAC50-SF1.0	50	1.0	58
RAC50-SF1.5	50	1.5	45
RAC100-SF0	100	0.0	82
RAC100-SF0.5	100	0.5	64
RAC100-SF1.0	100	1.0	42
RAC100-SF1.5	100	1.5	35

Figure 4.1 shows the variation of slump with steel fibre content at the four replacement levels.

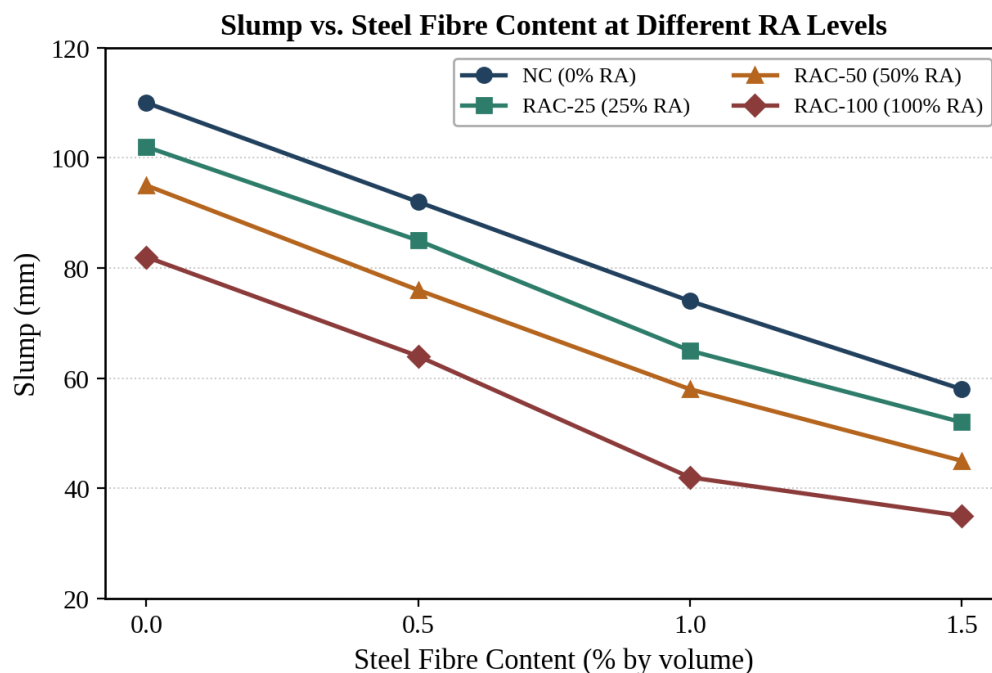


Figure 4.1: Variation of slump with steel fibre content at different recycled-aggregate levels

The slump decreased with both increasing recycled-aggregate content and increasing fibre dosage. For the natural-aggregate control, the slump fell from 110 mm at 0% fibre to 58 mm at 1.5% fibre, while at any given fibre dosage the slump decreased as the replacement level rose, reaching a minimum of 35 mm for the RAC100-SF1.5 mix. Two distinct mechanisms are responsible. The reduction with recycled-aggregate content arises from the rough, angular, and highly absorptive surface of the recycled aggregate: its adhered mortar absorbs part of the mixing water and increases inter-particle friction, reducing the free water available to lubricate flow. The reduction with fibre content arises because the randomly oriented fibres interlock with one another and with the aggregate, increasing the internal friction and yield stress of the mix and restraining its free movement. All mixes nevertheless remained cohesive and placeable with the aid of the superplasticiser. The progressive loss of workability with both variables is consistent with the observations of Kou and Poon (2015) for recycled aggregate concrete and of Afroughsabet and Ozbakkaloglu (2015) for steel fibre concrete.

4.2 Compressive Strength

The compressive strengths at 7 and 28 days are presented in Table 4.2 and illustrated in Figure 4.2.

Table 4.2: Compressive Strength Results

Mix ID	7-Day (MPa)	28-Day (MPa)
NC-SF0	32.1	43.8
NC-SF0.5	33.5	45.8
NC-SF1.0	35.3	48.5
NC-SF1.5	34.2	46.8
RAC25-SF0	30.0	40.8
RAC25-SF0.5	31.3	42.6
RAC25-SF1.0	33.2	45.3
RAC25-SF1.5	32.2	44.0

Mix ID	7-Day (MPa)	28-Day (MPa)
RAC50-SF0	27.8	38.1
RAC50-SF0.5	29.5	39.9
RAC50-SF1.0	31.3	42.3
RAC50-SF1.5	30.2	41.0
RAC100-SF0	25.1	35.1
RAC100-SF0.5	26.8	36.9
RAC100-SF1.0	28.8	39.3
RAC100-SF1.5	27.6	38.0

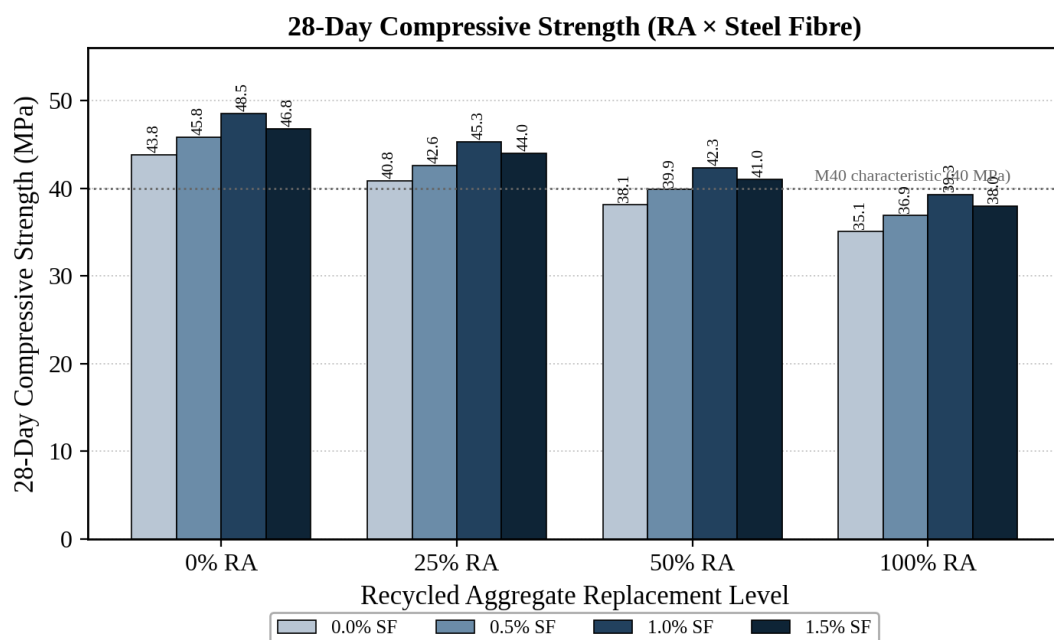


Figure 4.2: 28-day compressive strength for the recycled-aggregate and steel-fibre combinations

The compressive strength was governed by the opposing influences of the two variables. At every fibre dosage, the 28-day strength decreased as the recycled-aggregate content increased: at 1.0% fibre, for example, it fell from 48.5 MPa for the natural control to 45.3, 42.3, and 39.3 MPa at 25%, 50%, and 100% replacement, corresponding to reductions of 6.6%, 12.8%, and 19.0% relative to the natural-aggregate mix. This reduction is a direct consequence of the inferior recycled aggregate. Its adhered mortar is porous and micro-cracked, so the aggregate itself is weaker and more readily fractured; in addition, the recycled aggregate introduces a second, weaker interfacial transition zone between the old and new mortar, which acts as a preferential path for crack propagation under load. Both effects lower the load at which the matrix fails, and both become more pronounced as more natural aggregate is replaced.

Within each replacement level, the strength increased with fibre content up to 1.0% and then decreased at 1.5%. For the natural control the 28-day strength rose from 43.8 MPa at 0% fibre to a maximum of 48.5 MPa at 1.0% fibre, an improvement of 10.7%, before falling to 46.8 MPa at 1.5%; the same pattern, with gains of about 11–12% at 1.0% fibre, was observed at every replacement level. The initial increase reflects the confinement and crack-bridging action of the fibres, which restrain the lateral expansion of the specimen and delay the coalescence of micro-cracks into a continuous failure plane, allowing higher loads to be sustained. The decrease at 1.5% is attributed to the reduced workability and the onset of fibre balling at high dosage, which impair compaction and

entrap additional voids, so that the loss of compaction outweighs the confinement benefit. It should be noted that the margin between the 1.0% and 1.5% dosages is modest (of the order of 1.3–1.7 MPa, or about 3%); the identification of 1.0% as the optimum is therefore based on the highest mean strength obtained at each replacement level rather than on a formal test of statistical significance.

The control 28-day strength of 43.8 MPa exceeds the characteristic strength of 40 MPa, indicating that the base mix meets the M40 requirement in terms of mean strength; only the natural mix at 1.0% fibre (48.5 MPa) reaches the design target mean of 48.25 MPa. As all strengths reported in this study are the mean of three specimens, compliance is assessed here on the basis of mean strength; a formal characteristic-strength verification (mean less 1.65 times the standard deviation) would require the individual specimen values and is identified as a recommended extension in Chapter 5. The 7-day strengths were a consistent 71.5–74.0% of the 28-day values (mean 73%) across all mixes, reflecting the gradual strength gain of Portland Slag Cement. The optimum fibre content of 1.0% is in close agreement with Zhang et al. (2023) and Guo et al. (2018).

4.3 Split Tensile Strength

The split tensile strengths at 7 and 28 days are presented in Table 4.3 and illustrated in Figure 4.3.

Table 4.3: Split Tensile Strength Results

Mix ID	7-Day (MPa)	28-Day (MPa)
NC-SF0	2.85	3.85
NC-SF0.5	3.03	4.08
NC-SF1.0	3.25	4.35
NC-SF1.5	3.13	4.21
RAC25-SF0	2.63	3.58
RAC25-SF0.5	2.83	3.81
RAC25-SF1.0	3.05	4.05
RAC25-SF1.5	2.95	3.93
RAC50-SF0	2.43	3.31
RAC50-SF0.5	2.61	3.55
RAC50-SF1.0	2.85	3.81
RAC50-SF1.5	2.73	3.69
RAC100-SF0	2.15	2.98
RAC100-SF0.5	2.35	3.21
RAC100-SF1.0	2.61	3.45
RAC100-SF1.5	2.49	3.33

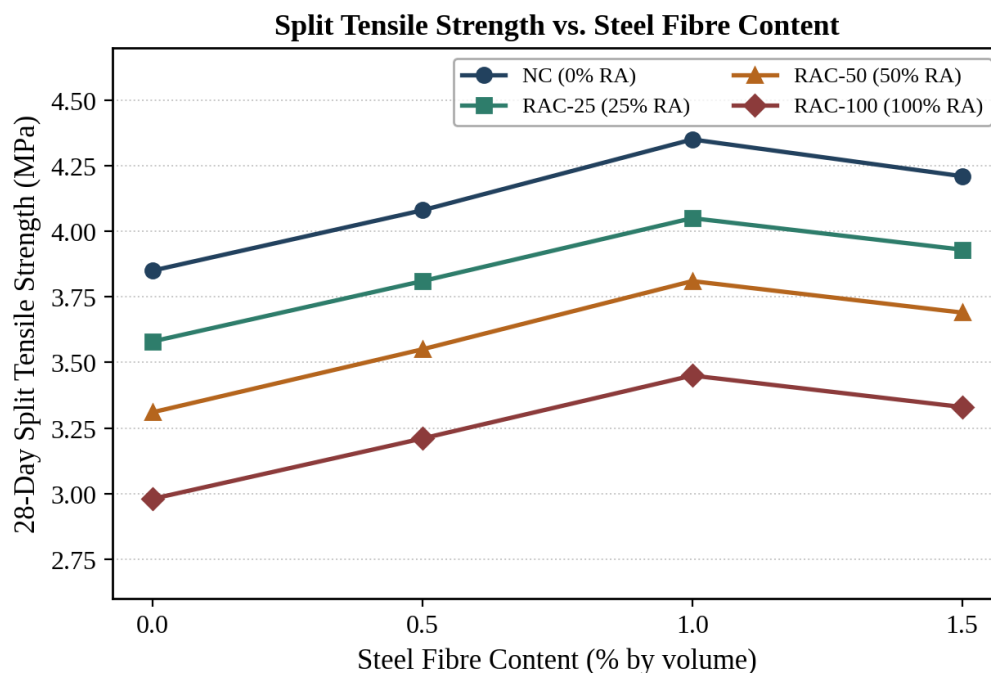


Figure 4.3: Variation of 28-day split tensile strength with steel fibre content

The split tensile strength followed the same overall pattern as the compressive strength — decreasing with recycled-aggregate content and peaking at 1.0% fibre — but the fibres had a proportionally greater effect in tension. At 1.0% fibre the 28-day tensile strength increased by about 13% for the natural control (from 3.85 to 4.35 MPa) and by about 16% for the 100% recycled mix (from 2.98 to 3.45 MPa). This larger relative benefit arises because tensile behaviour is governed primarily by crack bridging rather than by matrix strength: when a splitting crack forms, the fibres crossing it transfer tensile stress across its faces through their anchored ends, resisting crack opening and enabling the specimen to carry additional load after the matrix has cracked. Because the recycled-aggregate mixes are more crack-prone, the crack-bridging contribution of the fibres is proportionally more valuable in them, which is why the tensile gains are largest at the highest replacement level. The transition from a brittle splitting failure in the fibre-free mixes to a more ductile failure in which the cracked halves remained connected by bridging fibres was observed throughout, in agreement with Zhang et al. (2023) and Yoo and Banthia (2016).

Expressed relative to the compressive strength, the split tensile strength corresponds to a coefficient k in the relation $f_{ct} = k\sqrt{f_c}$ ranging from 0.50 to 0.63 across the sixteen mixes, with a mean of 0.57. This is in close agreement with the value of 0.56 given by the ACI relation for normal-weight concrete, confirming that the recycled-aggregate mixes retain a conventional tensile–compressive relationship. The coefficient increased consistently with fibre dosage — for example from 0.58 to 0.62 for the natural mix between 0% and 1.0% fibre — quantifying the disproportionate benefit of the fibres in tension noted above.

4.4 Flexural Strength

The flexural strengths at 7 and 28 days are presented in Table 4.4 and illustrated in Figure 4.4.

Table 4.4: Flexural Strength Results

Mix ID	7-Day (MPa)	28-Day (MPa)
NC-SF0	4.14	5.36
NC-SF0.5	4.36	5.62
NC-SF1.0	4.66	5.96

Mix ID	7-Day (MPa)	28-Day (MPa)
NC-SF1.5	4.52	5.80
RAC25-SF0	3.86	5.00
RAC25-SF0.5	4.12	5.26
RAC25-SF1.0	4.40	5.60
RAC25-SF1.5	4.26	5.44
RAC50-SF0	3.56	4.62
RAC50-SF0.5	3.80	4.88
RAC50-SF1.0	4.06	5.20
RAC50-SF1.5	3.94	5.04
RAC100-SF0	3.16	4.14
RAC100-SF0.5	3.42	4.40
RAC100-SF1.0	3.72	4.74
RAC100-SF1.5	3.58	4.58

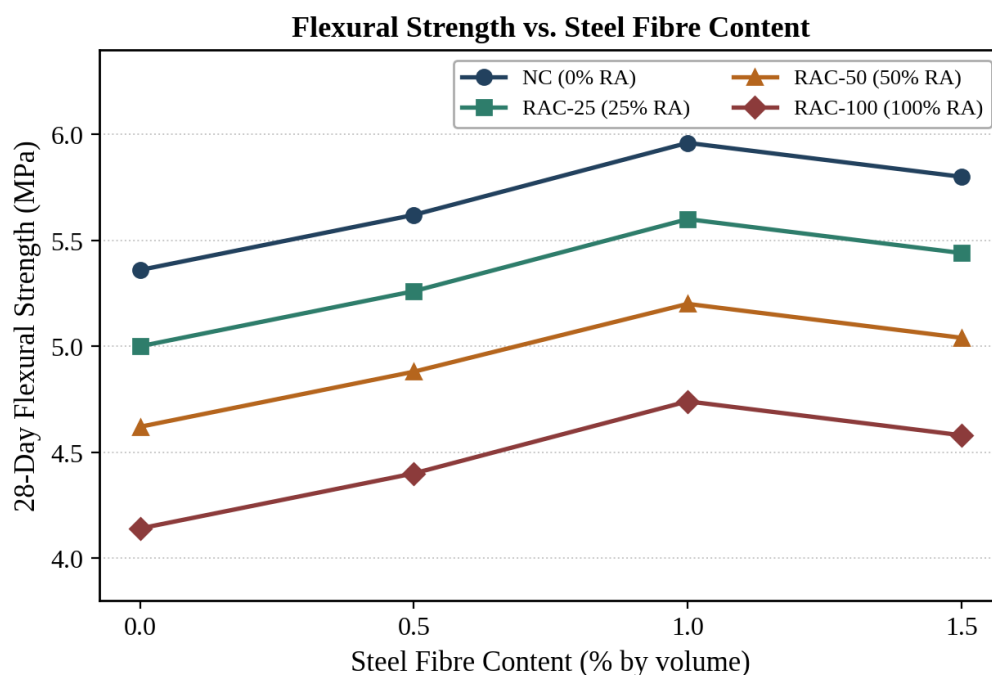


Figure 4.4: Variation of 28-day flexural strength with steel fibre content

The flexural strength again decreased with recycled-aggregate content and peaked at 1.0% fibre. At the optimum dosage the 28-day flexural strength rose from 5.36 to 5.96 MPa for the natural control and from 4.14 to 4.74 MPa for the fully recycled mix. Flexural strength is strongly enhanced by fibres because bending produces a zone of pure tension at the soffit of the beam, where crack bridging is most effective: as the extreme tensile fibre cracks, the steel fibres spanning the crack carry tensile force and generate a resisting moment, delaying the propagation of the crack towards the neutral axis and allowing the beam to sustain a higher load. The marked flexural improvement and the associated ductile failure mode are consistent with the findings of Ali and Qureshi (2019) and Guo et al. (2018).

The measured flexural strengths can be compared with the modulus of rupture predicted by the IS 456:2000 expression $f_{cr} = 0.7\sqrt{f_{ck}}$. Back-calculating the coefficient k in $f_b = k\sqrt{f_c}$ gives values of 0.70 to 0.86 across the sixteen mixes, so that the measured strengths range from equal to the code prediction for the weakest fully-recycled fibre-free mix (a ratio of 1.00) up to about 22% above it for the natural mix at 1.0% fibre (a ratio of 1.22). Two clear trends emerge: the coefficient decreases with recycled-aggregate content, because the weaker recycled aggregate and its interfacial zones reduce the flexural capacity towards the code lower bound, and it increases with fibre content, because the crack-bridging fibres raise the modulus of rupture above the plain-concrete value assumed by the code. The IS 456 expression, which does not account for fibre reinforcement, therefore provides a conservative estimate for all the fibre-reinforced mixes.

4.5 Rebound Hammer Test

The rebound numbers measured on the cubes at 7 and 28 days are presented in Table 4.5 and illustrated in Figure 4.5.

Table 4.5: Rebound Hammer Test Results

Mix ID	7-Day Rebound No.	28-Day Rebound No.
NC-SF0	32	42
NC-SF0.5	34	44
NC-SF1.0	35	45
NC-SF1.5	34	44
RAC25-SF0	30	40
RAC25-SF0.5	31	41
RAC25-SF1.0	33	43
RAC25-SF1.5	32	42
RAC50-SF0	28	37
RAC50-SF0.5	29	38
RAC50-SF1.0	31	40
RAC50-SF1.5	30	39
RAC100-SF0	25	34
RAC100-SF0.5	26	35
RAC100-SF1.0	28	37
RAC100-SF1.5	27	36

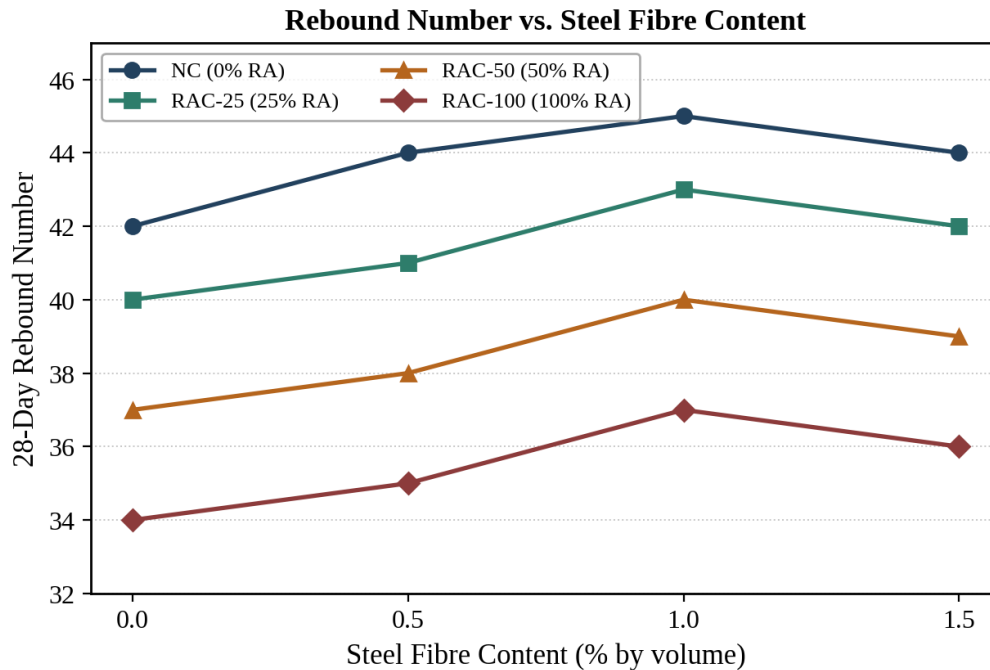


Figure 4.5: Variation of 28-day rebound number with steel fibre content

The rebound number mirrored the compressive-strength behaviour, decreasing with recycled-aggregate content and peaking at 1.0% fibre. At 28 days it ranged from 34 for the fully recycled fibre-free mix to 45 for the natural mix at 1.0% fibre. Since the rebound number reflects surface hardness, which is governed by the stiffness and density of the near-surface matrix, the more porous recycled-aggregate concrete produced lower rebound values, while the fibres, by refining the pore structure and restraining surface micro-cracking, raised them up to the optimum dosage; the slight reduction at 1.5% fibre is consistent with the reduced compaction at that dosage. As shown quantitatively in Section 4.8, the rebound number correlated strongly with the measured compressive strength, confirming its usefulness as a rapid, non-destructive indicator of relative concrete quality for both natural and recycled-aggregate mixes.

4.6 Water Absorption

The 28-day water absorption of all sixteen mixes is presented in Table 4.6 and illustrated in Figure 4.6.

Table 4.6: Water Absorption Results (28 days)

Mix ID	Water Absorption (%)	Mix ID	Water Absorption (%)
NC-SF0	1.82	RAC50-SF0	2.54
NC-SF0.5	1.76	RAC50-SF0.5	2.40
NC-SF1.0	1.72	RAC50-SF1.0	2.32
NC-SF1.5	1.68	RAC50-SF1.5	2.28
RAC25-SF0	2.15	RAC100-SF0	3.05
RAC25-SF0.5	2.05	RAC100-SF0.5	2.90
RAC25-SF1.0	2.00	RAC100-SF1.0	2.78
RAC25-SF1.5	1.94	RAC100-SF1.5	2.73

Figure 4.6 shows the variation of water absorption with steel fibre content at the four replacement levels.

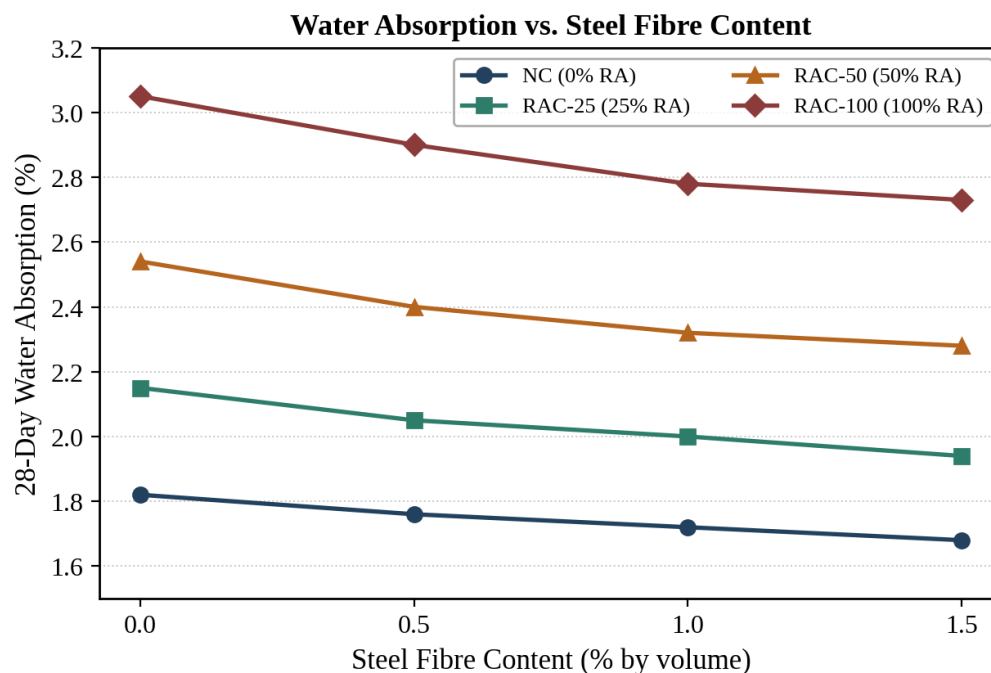


Figure 4.6: Variation of 28-day water absorption with steel fibre content

Water absorption increased markedly with recycled-aggregate content, from 1.82% for the fibre-free natural mix to 2.15%, 2.54%, and 3.05% at 25%, 50%, and 100% replacement respectively — an increase of about 68% at full replacement. This is the clearest expression of the inferior quality of the recycled aggregate: the porous, micro-cracked adhered mortar and the additional interfacial zones create a more open pore structure through which water is readily absorbed, which is also the underlying cause of the reduced strength and durability. The addition of steel fibres produced a modest reduction in water absorption at every replacement level, because the fibres restrict the widening and interconnection of micro-cracks and thereby refine the effective pore network. Even so, the water absorption of the recycled mixes remained above that of the natural mixes, confirming that fibres mitigate but do not eliminate the durability penalty of recycled aggregate. The increase of water absorption with replacement level is fully consistent with the durability observations of Thomas et al. (2018) and Poon, Shui and Lam (2004).

4.7 Comparative Assessment and Optimum Combination

To synthesise the results, the effect of recycled-aggregate replacement at the optimum fibre dosage, and the effect of fibre addition at each replacement level, are summarised in Tables 4.7 and 4.8, and the compensating role of the fibres is illustrated in Figure 4.7.

Table 4.7: Effect of Recycled-Aggregate Replacement at 1.0% Fibre (28-day)

RA Level	Compressive (MPa)	Reduction vs. NC-SF1.0 (%)	Comparison with Plain NC-SF0 (43.8 MPa)
0% (NC-SF1.0)	48.5	—	+10.7%
25% (RAC25-SF1.0)	45.3	6.6	+3.4%
50% (RAC50-SF1.0)	42.3	12.8	-3.4%
100% (RAC100-SF1.0)	39.3	19.0	-10.3%

Table 4.7 conveys the central finding of the study. At the 1.0% fibre dosage, the 25% recycled mix (45.3 MPa) exceeded the plain natural-aggregate control (43.8 MPa) by 3.4%, while the 50% recycled mix (42.3 MPa) recovered to within 3.4% of it. In other words, the crack-bridging and confinement action of 1.0% steel fibre fully offsets the strength lost by replacing one quarter of the

natural coarse aggregate, and offsets most of the loss at 50% replacement, leaving only a small net deficit of about 3%. At full (100%) replacement the fibre-compensated strength (39.3 MPa) fell about 10% below the plain control and marginally below the 40 MPa M40 characteristic value; full replacement therefore remains feasible but does not fully recover the reference strength. This behaviour is displayed in Figure 4.7.

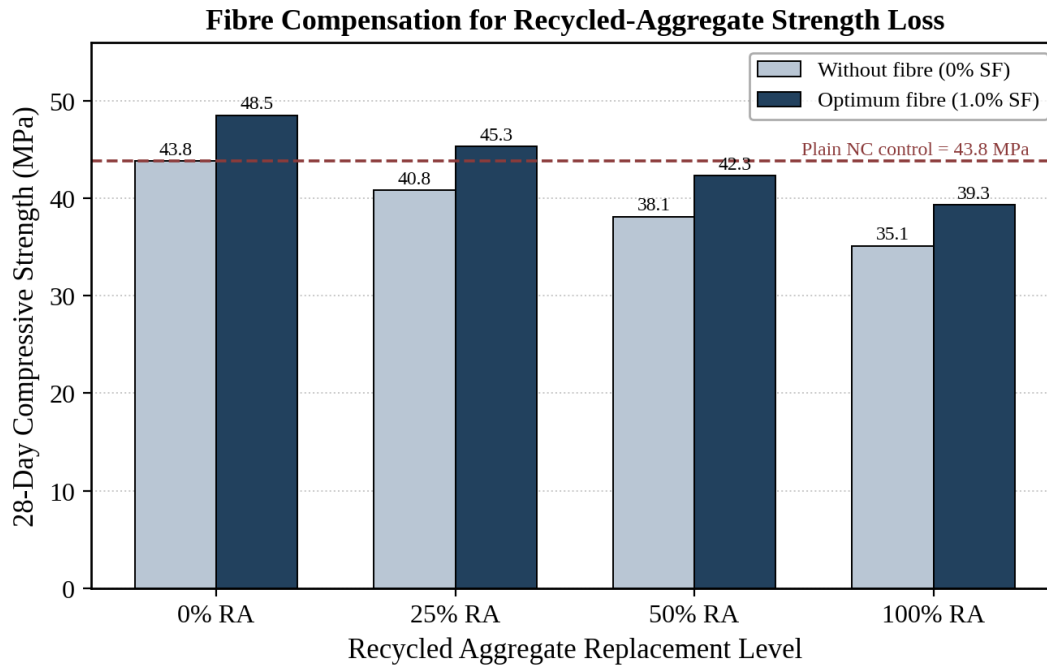


Figure 4.7: Compensation of recycled-aggregate strength loss by 1.0% steel fibre

Figure 4.7 compares, for each replacement level, the 28-day compressive strength of the fibre-free mix with that of the 1.0%-fibre mix, against the plain natural-control datum. The fibre-reinforced 25% and 50% mixes reach or approach the control line, whereas the fibre-free mixes lie progressively below it, visually confirming the compensating action of the fibres. The corresponding fibre-induced improvements in all three mechanical properties are summarised in Table 4.8.

Table 4.8: Improvement due to 1.0% Steel Fibre relative to the Fibre-Free Mix (28-day)

RA Level	Compressive Gain (%)	Split Tensile Gain (%)	Flexural Gain (%)
0% (NC)	+10.7	+13.0	+11.2
25% (RAC25)	+11.0	+13.1	+12.0
50% (RAC50)	+11.0	+15.1	+12.6
100% (RAC100)	+12.0	+15.8	+14.5

Table 4.8 shows that the fibre-induced improvement was consistent across all replacement levels and was greatest, in relative terms, for the split tensile strength and for the highest recycled-aggregate content — precisely where the crack-bridging action of the fibres is most needed. Considering all the results together, a steel fibre dosage of 1.0% by volume gave the highest mean compressive strength and the highest rebound number at every replacement level, together with substantial gains in tensile and flexural strength and a reduction in water absorption, while retaining acceptable workability; it is therefore adopted as the optimum dosage, subject to the reservation that the 1.0%–1.5% difference is modest and warrants confirmation against the specimen-to-specimen scatter (Section 4.8). On the basis of the compensation analysis, recycled-aggregate replacement of up to 50% combined with 1.0% steel fibre is recommended for structural M40 applications, since this combination recovers the mean compressive strength to within

about 3% of plain natural-aggregate concrete while conferring the environmental benefits of recycled-aggregate utilisation; full (100%) replacement remains feasible for less demanding applications where a strength reduction of about 10% relative to the plain control is acceptable.

4.8 Correlation and Statistical Analysis

To consolidate the experimental findings, the inter-relationships between the measured properties and the relative influence of the two design variables were examined quantitatively using the sixteen mix-average results. The linear (Pearson) correlation coefficients between the 28-day compressive strength and the other properties are presented in Table 4.9.

Table 4.9: Correlation of 28-Day Compressive Strength with Other Properties (n = 16)

Property	Correlation Coefficient, r	Coefficient of Determination, R ²
Flexural strength	+0.998	0.996
Split tensile strength	+0.996	0.992
Rebound number	+0.989	0.979
Water absorption	−0.949	0.901
Slump	+0.095	0.009

Table 4.9 shows that the compressive strength is very strongly and positively correlated with the flexural strength, split tensile strength, and rebound number, and strongly and negatively correlated with water absorption, so that a single underlying factor — the quality and density of the hardened matrix — governs all of these properties together. The strong inverse correlation with water absorption confirms that the more porous, higher-absorption recycled-aggregate mixes are also the weaker ones. By contrast, the negligible correlation with slump ($R^2 = 0.009$) shows that workability is decoupled from strength in this programme, because slump is controlled chiefly by the fibre content and aggregate texture rather than by the strength of the matrix. The correlation between compressive strength and the tensile and flexural strengths is shown in Figure 4.8.

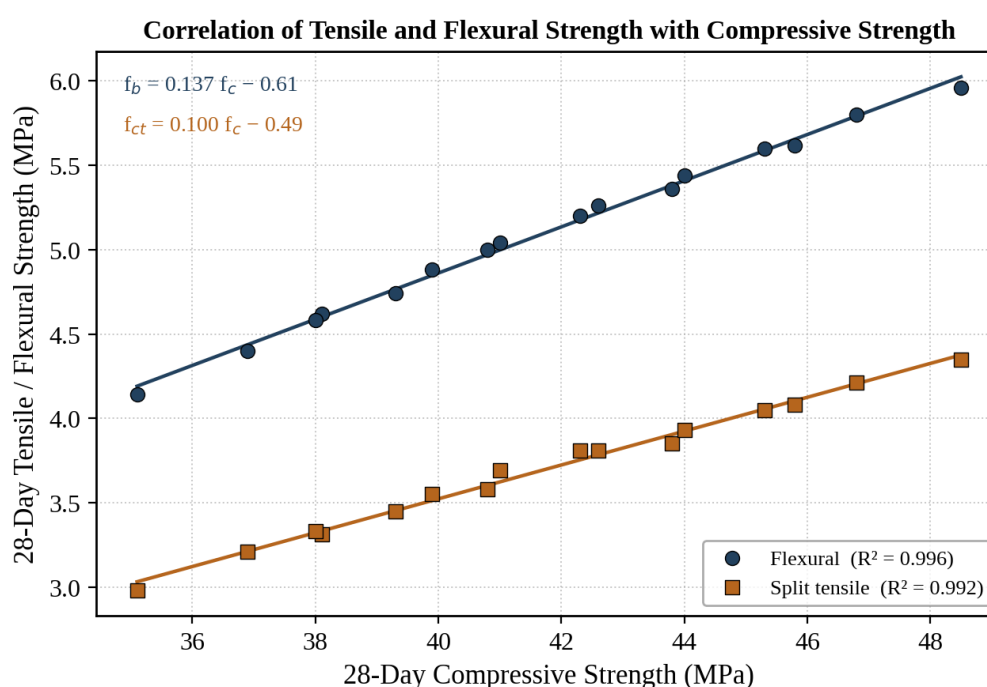


Figure 4.8: Correlation of tensile and flexural strength with compressive strength

Figure 4.8 confirms the near-linear relationships and provides the best-fit expressions relating the tensile and flexural strengths to the compressive strength across the full range of mixes. These relationships, together with the code-coefficient analysis of Sections 4.3 and 4.4, allow the tensile and flexural strengths of the recycled-aggregate mixes to be estimated from their compressive strength with confidence.

The relative contributions of recycled-aggregate replacement and steel fibre dosage to the total variation in each property were estimated by partitioning the sum of squares of the 4×4 matrix of mean results between the two main effects and a residual term. The results, expressed as the percentage of the total variance attributable to each source, are presented in Table 4.10.

Table 4.10: Partition of Variance between Recycled Aggregate and Steel Fibre (η^2 , %)

Property	Recycled Aggregate (%)	Steel Fibre (%)	Residual (%)
Compressive strength	80.7	19.2	0.1
Split tensile strength	76.5	23.4	0.1
Flexural strength	80.9	19.1	0.0
Water absorption	95.4	4.2	0.4
Rebound number	88.7	11.0	0.3
Slump	22.6	77.1	0.3

Table 4.10 quantifies the roles of the two variables. Recycled-aggregate replacement is by far the dominant influence on compressive, split tensile, and flexural strength (about 77–81% of the variance), on rebound number (89%), and on water absorption (95%), whereas steel fibre content is the dominant influence on workability, accounting for 77% of the variation in slump. The very small residual term in every case (below 0.5%) indicates that the two variables act in an essentially additive manner, with little interaction between them over the range studied. It must be emphasised, however, that this decomposition is based on the mean result of each mix; because only one mean value was available per cell, the residual term combines the true interaction with experimental error, and the partition should therefore be read as a descriptive measure of the relative importance of the two factors rather than as a formal test of statistical significance.

Finally, the limitations of the present analysis should be recognised. All results are the mean of three specimens, and the individual specimen values were not available for the statistical treatment; consequently, standard deviations, confidence intervals, and characteristic strengths could not be computed, and the analyses of variance and correlation reported above rest on the mix means alone. Formal significance testing of the main effects and their interaction, post-hoc comparison of the fibre dosages, and a rigorous characteristic-strength assessment for M40 compliance would require the individual specimen readings. These, together with microstructural and durability investigations, are identified as priorities for future work in Chapter 5.

CHAPTER 5

CONCLUSIONS AND FUTURE SCOPE

5.1 General

This study investigated the fresh, mechanical, non-destructive, and durability-related behaviour of M40 grade Steel Fibre Reinforced Recycled Aggregate Concrete through a full 4×4 factorial programme covering four recycled-aggregate replacement levels (0%, 25%, 50%, and 100%) and four steel fibre dosages (0%, 0.5%, 1.0%, and 1.5% by volume). The principal conclusions drawn from the experimental results are set out below, followed by recommendations for future research.

5.2 Conclusions

1. The base M40 mix was validated by the natural-aggregate control, whose mean 28-day compressive strength of 43.8 MPa exceeded the characteristic strength of 40 MPa, confirming the adequacy of the mix design carried out in accordance with IS 10262:2019. As all reported strengths are triplicate means, compliance was assessed on a mean-strength basis.
2. Workability decreased with both recycled-aggregate content and steel fibre dosage. The slump fell from 110 mm for the plain natural mix to 35 mm for the fully recycled mix at 1.5% fibre, owing to the high absorption and rough texture of the recycled aggregate and the inter-particle interlock introduced by the fibres. All mixes nevertheless remained cohesive and placeable with the superplasticiser.
3. Recycled-aggregate replacement systematically reduced the compressive, split tensile, and flexural strengths. At 1.0% fibre, the 28-day compressive strength decreased by 6.6%, 12.8%, and 19.0% at 25%, 50%, and 100% replacement respectively, as a result of the porous adhered mortar and the additional weak interfacial transition zones of the recycled aggregate.
4. Steel fibre addition improved all mechanical properties up to a dosage of 1.0%, beyond which a slight reduction occurred at 1.5% owing to fibre balling and reduced compaction. A steel fibre content of 1.0% by volume, which gave the highest mean strength at every replacement level, is therefore adopted as the optimum dosage, although the margin over the 1.5% dosage (about 3% in compression) is modest.
5. At the 1.0% dosage, the fibre-induced improvements were consistent across all replacement levels, amounting to about 11–12% in compressive strength, 13–16% in split tensile strength, and 11–15% in flexural strength, with the largest relative gains occurring in tension and at the highest recycled-aggregate content, where the crack-bridging action of the fibres is most effective.
6. Steel fibres largely compensated for the strength loss caused by recycled aggregate. With 1.0% fibre, the 25% recycled mix (45.3 MPa) exceeded the plain natural control (43.8 MPa) by 3.4%, and the 50% recycled mix (42.3 MPa) recovered to within 3.4% of it; only at full replacement (39.3 MPa) did the fibre-compensated strength fall appreciably (about 10%) below the plain control and marginally below the 40 MPa M40 characteristic value.
7. The rebound number (34–45 at 28 days) mirrored the compressive-strength trend, decreasing with recycled-aggregate content and peaking at 1.0% fibre, and confirmed the relative quality ranking of the mixes as a rapid non-destructive check.
8. Water absorption increased by up to 68% at full replacement, confirming the durability penalty of recycled aggregate; steel fibres reduced water absorption modestly at every level by refining the crack network, but did not fully offset the effect of the recycled aggregate.
9. Correlation and variance analysis of the results showed that compressive strength is very strongly correlated with flexural strength, split tensile strength, and rebound number, and inversely with water absorption, and that recycled-aggregate

replacement accounts for the majority of the variation in strength, rebound, and absorption (about 77–95%), whereas steel fibre content dominates the variation in workability (77%); the two factors act in an essentially additive manner.

10. Overall, M40 concrete incorporating up to 50% recycled coarse aggregate together with 1.0% steel fibre by volume is recommended for structural applications, as it recovers the mean compressive strength to within about 3% of plain natural-aggregate concrete while delivering the environmental benefits of recycled-aggregate utilisation; full replacement remains suitable for less demanding uses where a strength reduction of about 10% is acceptable.

5.3 Future Scope

The present work may be extended in the following directions:

- Statistical analysis of the individual specimen results — standard deviations, confidence intervals, characteristic strengths, and a full two-way analysis of variance with post-hoc comparison — to establish the statistical significance of the observed recycled-aggregate and fibre effects and to place the identification of the optimum dosage and the assessment of M40 compliance on a formal inferential basis.
- Independent non-destructive evaluation, including direct Ultrasonic Pulse Velocity measurement, to complement the rebound-hammer and destructive results and to develop calibrated strength–NDT correlations for recycled-aggregate concrete.
- Evaluation of long-term durability through rapid chloride penetration, sulphate attack, carbonation, and freeze–thaw testing, to complement the water absorption results obtained here.
- Microstructural investigation of the interfacial transition zones and fibre–matrix bond using scanning electron microscopy, to relate the observed mechanical behaviour directly to the microstructure.
- Assessment of the modulus of elasticity, stress–strain response, toughness, and post-cracking load–deflection behaviour of SFRRAC, which were inferred from the strength results in this study but not measured directly.
- Study of alternative fibre types, hybrid fibre systems, and higher aspect ratios, and of two-stage mixing or aggregate pre-treatment to further improve the recycled-aggregate mixes.
- Full-scale structural testing of beams, slabs, and pavements, together with a life-cycle cost and environmental-impact assessment, to support the adoption of SFRRAC in practice.

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APPENDIX A

MIX DESIGN CALCULATIONS

This appendix summarises the M40 mix-design calculation carried out in accordance with IS 10262:2019, on which the base mix proportions in Chapter 3 are based.

A.1 Design Stipulations

- Grade designation: M40
- Type of cement: Portland Slag Cement (IS 455:2015)
- Maximum nominal size of aggregate: 20 mm
- Exposure condition: Severe (reinforced concrete)
- Workability: 75–100 mm slump (natural-aggregate control)
- Method of placing: vibrated on a table
- Chemical admixture: polycarboxylate-ether superplasticiser

A.2 Target Mean Strength

For M40 with an assumed standard deviation of 5 MPa (IS 10262:2019), the target mean strength is $f'_{ck} = 40 + 1.65 \times 5 = 48.25$ MPa.

A.3 Selection of Water–Cement Ratio and Water Content

A free water–cement ratio of 0.40 was adopted, satisfying the durability limit for severe exposure. Starting from the IS 10262 reference water content for 20 mm aggregate and applying a water reduction of approximately 20% through the superplasticiser, the free water content was taken as 152 kg/m³.

A.4 Cement Content

The cement content is the water content divided by the water–cement ratio: $152 / 0.40 = 380$ kg/m³, which exceeds the minimum cement content prescribed for severe exposure.

A.5 Aggregate Content and Recycled-Aggregate Replacement

Using the absolute-volume method with the measured specific gravities, and the volume fractions of coarse and fine aggregate appropriate to a 20 mm aggregate and Zone II sand, the fine and coarse aggregate contents were obtained as 684 kg/m³ and 1277 kg/m³ respectively. For the recycled-aggregate mixes, the natural coarse aggregate was replaced by recycled coarse aggregate on a one-to-one mass basis at 25%, 50%, and 100%, the recycled aggregate being used in the pre-soaked, saturated surface-dry condition to offset its higher absorption.

A.6 Steel Fibre Content

The steel fibre content was calculated as a volume fraction of concrete, the mass being obtained by multiplying by the fibre density of 7850 kg/m³. The 0.5%, 1.0%, and 1.5% dosages therefore correspond to 39.25, 78.50, and 117.75 kg/m³ respectively.

A.7 Final Mix Proportions

The final proportions of the base M40 mix resulting from the above calculation are summarised in Table A.1.

Table A.1: Final Mix Proportions of the Base M40 Concrete

Material	Quantity (kg/m ³)	Ratio by Mass
Cement (PSC)	380	1.00
Water	152	0.40
Fine Aggregate	684	1.80
Coarse Aggregate	1277	3.36
Superplasticiser	3.80	0.01

The resulting nominal mix proportion is 1 : 1.80 : 3.36 at a water–cement ratio of 0.40, as used throughout the experimental programme described in Chapter 3.