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Research Article

Experimental Study on Mechanical, Durability, And Environmental Performance of RCA-Based High-Strength Concrete

Devesh Ojha [1*], Ankit Yadav [2], Rajendra Kumar Srivastava [3]

[1] Department of Civil Engineering, Amity School of Engineering and Technology, Amity University, Lucknow, Uttar Pradesh, India

[2] Department of Civil Engineering, Amity School of Engineering and Technology, Amity University, Lucknow, Uttar Pradesh, India

[3] Retired Engineer in Chief UP P.W.D. and Retired M.D. U.P. Bridge Corporation, Lucknow, Uttar Pradesh, India

Corresponding Author: * Devesh Ojha

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Abstract

The global construction industry stands as one of the most resource-intensive sectors, consuming vast quantities of raw materials, energy, and water. Among these, concrete remains the most extensively used man-made material, second only to water in global consumption. Its widespread application, however, comes at a significant environmental cost. The extraction of natural aggregates from quarries and riverbeds has led to large-scale depletion of non-renewable resources, land degradation, and ecological imbalance. Concurrently, the generation of construction and demolition waste (CDW) has escalated with rapid urbanization, resulting in severe waste management challenges and unsustainable landfill burdens. In this context, the utilization of recycled aggregates (RA) derived from processed demolition debris presents a promising pathway toward sustainable construction. Replacing natural coarse aggregates (NCA) with recycled coarse aggregates (RCA) in concrete not only reduces the strain on natural resources but also offers a practical solution for the effective reuse of CDW. This study, titled *"Use of Recycled Aggregates in High-Strength Concrete: A Sustainable Approach for Modern Construction,"* investigates the mechanical and durability performance of high-strength concrete (HSC) incorporating varying proportions of RCA. The experimental program was designed to evaluate the influence of RCA replacement levels (0%, 20%, 30%, and 50%) on compressive strength**,** chloride ion permeability**,** and overall durability. The concrete was mixed to achieve a characteristic compressive strength of M60 using Ordinary Portland Cement (OPC 53 Grade)**,** natural river sand as fine aggregate, and RCA obtained from crushed M30-grade concrete waste. A constant water–cement ratio of 0.35 was maintained across all mixes. Tests were conducted at 7, 14, and 28 days to assess the development of mechanical strength, while the Rapid Chloride Penetration Test (RCPT) evaluated the permeability resistance of each mix after 28 days of curing. Results indicate that up to 30% replacement of NCA with RCA yields compressive strengths comparable to those of conventional concrete, with a marginal reduction of approximately 8–10%. Beyond this threshold, a noticeable decrease in strength and density was observed, primarily attributed to the higher porosity and weaker interfacial transition zone (ITZ) of the recycled aggregates. Durability assessments revealed that chloride ion permeability increased with RCA content; however, the RCPT results for 30% RCA mix remained within the "low permeability" category as per ASTM C1202 standards. From a sustainability standpoint, the inclusion of 30% RCA led to a 15–18% reduction in CO_2 emissions**,** 30% conservation of natural aggregate resources**,** and a measurable decline in embodied energy compared to traditional HSC. The study thus demonstrates that with appropriate quality control, surface treatment of RCA, and optimized mix design, recycled aggregates can be successfully incorporated into structural-grade high-strength concrete without compromising performance or longevity. Overall, this research underscores the vital role of recycled aggregates in achieving circular economy objectives within the construction sector. It provides evidence-based insights into the technical viability, environmental benefits, and potential policy implications of adopting RCA as a mainstream material for sustainable and resilient infrastructure development.

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KEYWORDS: Recycled aggregates, high-strength concrete, sustainability, compressive strength, durability, chloride permeability, circular construction

1. INTRODUCTION

1.1 GENERAL OVERVIEW

Concrete is the backbone of modern infrastructure — a composite material that has revolutionized construction across the world. Its widespread use is attributed to its excellent compressive strength, workability, and adaptability to various architectural and structural forms. However, this heavy reliance on concrete has led to immense consumption of natural aggregates (NA) such as crushed rock, gravel, and sand, which together account for nearly 70–80% of the total concrete volume. The increasing urbanization, industrial growth, and demand for housing have resulted in exponential extraction of these aggregates, exerting significant pressure on the Earth's limited natural resources. At the same time, the construction and demolition (C&D) sector contributes millions of tonnes of waste annually. Large volumes of concrete debris from demolished buildings, bridges, and pavements are disposed of in landfills or open spaces, causing environmental degradation and occupying valuable land resources. In India alone, it is estimated that over 150 million tonnes of C&D waste are generated each year, of which less than 10% is effectively recycled or reused. This dual problem of resource depletion and waste accumulation calls for an urgent transformation toward sustainable practices in concrete technology. The concept of Recycled Aggregate Concrete (RAC) has emerged as a sustainable alternative, in which recycled coarse aggregates (RCA) derived from C&D waste partially or fully replace natural aggregates in concrete mixes. This approach not only helps reduce the burden on natural resources but also minimizes landfill usage and lowers carbon emissions associated with quarrying and transportation. Integrating RCA into high-strength concrete (HSC) can thus play a transformative role in realizing sustainable and circular construction systems.

1.2 NEED FOR AND IMPORTANCE OF THE STUDY

The depletion of natural aggregate reserves is not only an ecological concern but also a socioeconomic challenge. Quarrying operations disturb natural landscapes, lead to soil erosion, increase dust and noise pollution, and negatively impact nearby water bodies and habitats. Moreover, the energy-intensive processes involved in extraction and transportation of aggregates significantly contribute to greenhouse gas (GHG) emissions. Meanwhile, the accumulation of demolition debris represents a missed opportunity for resource recovery. Research conducted by the European Aggregates Association (UEPG) and various national agencies indicates that recycled materials can replace up to 25–30% of natural aggregates without major structural compromise. Yet, in most developing countries, the use of recycled aggregates remains minimal due to lack of awareness, quality control, and standardized guidelines. Therefore, this study seeks to address both environmental and practical needs by demonstrating the viability of using recycled aggregates in high-strength structural concrete, which has traditionally relied on premium quality materials. The goal is to bridge the gap between sustainability and performance, encouraging large-scale adoption of RCA in modern construction.

1.3 PROBLEM STATEMENT

Despite significant research and technological advancements, the acceptance of recycled aggregate concrete in mainstream construction remains limited. The major challenges include:

- **Variability in RCA quality:** Recycled aggregates often contain adhered mortar and micro-cracks, leading to increased porosity and water absorption.
- **Reduced mechanical strength:** High-strength concrete demands superior aggregate–cement bonding, which is sometimes compromised when RCA is used without treatment.
- **Durability concerns:** Issues like chloride ion penetration, carbonation, and shrinkage can be more pronounced in RAC, particularly in aggressive environments.
- **Lack of standardized design codes:** Absence of comprehensive guidelines for proportioning and performance evaluation restricts industrial-scale adoption.

This study aims to evaluate and overcome these limitations through controlled experimentation and detailed analysis of the performance of RCA in high-strength concrete.

1.4 SCOPE OF THE STUDY

The research focuses on assessing the strength, durability, and sustainability of high-strength concrete made with recycled coarse aggregates. The scope includes:

1. Investigating the effect of varying RCA replacement levels (0%, 20%, 30%, and 50%) on the mechanical and durability characteristics of M60-grade concrete.
2. Performing compressive strength tests and Rapid Chloride Penetration Tests (RCPT) to evaluate structural and durability performance.
3. Comparing the results with conventional concrete to establish optimum replacement levels.
4. Quantifying environmental benefits in terms of resource conservation, energy savings, and CO_2 emission reduction.
5. Providing recommendations for practical application and sustainable construction policy frameworks.

1.5 OBJECTIVES

The specific objectives of this research are as follows:

1. To understand the influence of recycled coarse aggregates on the strength development of high-strength concrete.
2. To evaluate the durability of RAC under chloride attack using RCPT and to assess its resistance to permeability.
3. To determine the optimum RCA replacement level that provides acceptable strength and durability performance.
4. To analyze the environmental impact of partial RCA substitution using sustainability indicators.
5. To propose a framework for incorporating RCA in structural applications consistent with sustainable construction practices.

1.6 SIGNIFICANCE OF THE STUDY

This research holds both scientific and practical significance. Scientifically, it contributes to the growing body of knowledge on recycled aggregate concrete by providing performance-based evidence for its use in high-strength structural applications—an area still underexplored. Practically, it supports sustainable construction objectives by demonstrating that quality-controlled RCA can serve as a viable replacement for natural aggregates without compromising essential engineering properties.

The study aligns with global sustainability goals, including:

- **UN Sustainable Development Goal (SDG) 11:** Sustainable cities and communities.
- **SDG 12:** Responsible consumption and production.
- **SDG 13:** Climate action.

In the long term, adopting RCA can lead to:

- Reduced dependence on virgin quarry materials.
- Conservation of natural landscapes and ecosystems.
- Decrease in construction waste generation and landfill pressure.
- Reduction in embodied energy and carbon emissions associated with concrete production.

Hence, the study not only strengthens the scientific foundation for recycled materials in concrete but also provides actionable insights for engineers, policymakers, and environmental planners.

2: LITERATURE REVIEW

2.1 INTRODUCTION

Concrete has been a fundamental material for infrastructure development for more than a century due to its exceptional compressive strength, moldability, and cost efficiency. However, the modern construction industry faces critical sustainability challenges associated with the extensive use of natural aggregates (NA) and the increasing volume of construction and demolition waste (CDW). In response, researchers worldwide have focused on utilizing recycled aggregates (RA), obtained from crushed concrete waste, as a partial or complete substitute for natural aggregates. The resulting material, known as Recycled Aggregate Concrete (RAC), not only addresses environmental concerns but also contributes to resource conservation and energy efficiency. This chapter presents a comprehensive review of published literature related to the mechanical, durability, and sustainability aspects of RAC, with a specific focus on high-strength applications. The review also identifies research gaps and sets the context for the experimental investigation carried out in this study.

2.2 RECYCLED AGGREGATES: ORIGIN AND CHARACTERISTICS

Recycled aggregates are obtained from processing construction and demolition debris such as demolished concrete structures, pavements, and precast components. The quality of recycled aggregates depends on multiple factors including the source of concrete, processing method, and adhered mortar content.

According to de Brito and Saikia (2013), recycled aggregates generally have:

- Higher water absorption (up to 8%),
- Lower specific gravity, and
- Higher porosity than natural aggregates, due to residual cement paste adhered to the surface.

These properties can adversely influence the fresh and hardened behavior of concrete, particularly workability, density, and compressive strength. However, with pre-treatment techniques such as mechanical abrasion, acid washing, or thermal treatment, the quality of RCA can be significantly improved.

Tam et al. (2008) demonstrated that washing and pre-soaking recycled aggregates reduce the influence of surface microcracks and improve the bond between the aggregate and cement paste. Similarly, Poon and Chan (2007) observed that replacing up to 30% of natural aggregates with RCA has a minimal effect on strength, provided that proper mix proportioning and water control are maintained.

2.3 GLOBAL SCENARIO OF AGGREGATE CONSUMPTION

According to data from the European Aggregates Association (UEPG, 2023), global demand for construction aggregates exceeded 50 billion tonnes per year, and the rate continues to grow by 4–5% annually. In most countries, aggregates represent nearly 85% of the total mineral extraction volume, surpassing coal, oil, and metal ores combined.

Despite this enormous demand, recycling rates remain low. The average proportion of recycled aggregates used in construction is:

- 7% across the European Union,
- 25% in the Netherlands,
- 18% in Belgium, and
- Less than 1% in most developing nations, including India.

This underutilization reflects the absence of standardized guidelines, market incentives, and public awareness. Incorporating recycled aggregates into high-strength concrete (HSC) represents a significant step toward bridging this gap and promoting circular economy principles in construction.

2.4 MECHANICAL PROPERTIES OF RAC

2.4.1 Compressive Strength

The compressive strength of RAC depends on the replacement ratio, quality of RCA, and mix design parameters.

- **Ahmed (2014)** studied the "dividing strength" phenomenon in RAC and reported that concrete containing RCA develops a two-phase relationship in strength — initially weaker due to porous ITZ, but gradually improving as hydration progresses.
- **Rahal (2007)** observed that the compressive strength of RAC can reach 90–95% of natural aggregate concrete (NAC) when replacement does not exceed 30%.
- **Mwasha and Ramnath (2018)** achieved compressive strengths above 80 MPa in HSC containing 100% RCA when pre-soaked aggregates and particle packing optimization were employed.

These findings suggest that RAC can achieve acceptable mechanical performance when designed with low water–cement ratios and proper surface treatments of RCA.

2.4.2 Modulus of Elasticity and Flexural Strength

Recycled aggregate concrete typically exhibits a 10–20% lower modulus of elasticity than NAC due to the lower stiffness of RCA.

Ajdukiewicz and Kliszczewicz (2007) reported that the flexural strength of RAC is less affected than its compressive strength, making it suitable for non-critical flexural elements such as slabs and pavements. The study emphasized the importance of aggregate interlock and optimized particle distribution to improve stiffness and deformation behavior.

2.4.3 Density and Workability

Due to the rough and irregular texture of RCA, RAC generally shows reduced workability. The higher water absorption capacity of RCA can be mitigated by:

- Pre-saturating aggregates before mixing, or
- Adjusting the effective water–cement ratio.

When such measures are applied, the slump and compaction characteristics of RAC can closely match those of NAC, even for high-performance concretes.

2.5 DURABILITY OF RAC

Durability is a key parameter for evaluating the long-term performance of recycled aggregate concrete, particularly in marine or chloride-rich environments.

2.5.1 Chloride Ion Penetration

Matias et al. (2014) performed RCPT tests on RAC mixes and reported that the chloride permeability increased with higher RCA content. Nevertheless, concretes with 30% RCA replacement still exhibited "low" to "very low" chloride ion permeability according to ASTM C1202 classification. The study also found that the use of superplasticizers and supplementary cementitious materials (SCMs) like silica fume or fly ash greatly improved the impermeability of RAC.

2.5.2 Water Absorption and Permeability

Levy and Helene (2004) demonstrated that RAC exhibits up to 15% higher water absorption compared to NAC. However, this can be effectively reduced through improved curing and aggregate grading. The presence of residual mortar in RCA increases capillary porosity, but also enhances internal curing, leading to better hydration of cement paste at later ages.

2.5.3 Carbonation and Shrinkage

Studies by Xiao et al. (2006) and Kou and Poon (2012) highlighted that the carbonation depth in RAC is typically higher than in NAC, particularly when RCA content exceeds 50%. However, superplasticizers and low w/c ratios effectively limit carbonation-induced deterioration. Similarly, drying shrinkage tends to be marginally higher for RAC due to the porous nature of recycled aggregates.

Overall, durability concerns can be mitigated through optimized design strategies, proper aggregate pre-treatment, and selection of suitable admixtures.

2.6 SUSTAINABILITY AND ENVIRONMENTAL BENEFITS

Recycling aggregates has a direct and measurable impact on sustainability indicators such as carbon emissions, energy use, and resource efficiency.

- Habert and Roussel (2009) demonstrated that replacing 30% of natural aggregates with RCA can reduce the embodied carbon footprint of concrete by 15–20%.
- Tam (2008) reported that RCA-based concrete could reduce transportation energy by 25–30%, especially when sourced locally.
- RILEM Technical Committee (2018) emphasized that recycling promotes a closed-loop construction system, reducing landfill waste and encouraging material circularity.

Furthermore, life-cycle assessments (LCA) show that RAC has a lower environmental impact when compared to conventional concrete, especially when recycled materials are sourced near urban construction sites.

2.7 RESEARCH GAPS IDENTIFIED

Based on the critical review of the literature, the following gaps have been identified:

1. **Limited studies on High-Strength Concrete (HSC):** Most previous work focuses on normal-strength concrete (20–40 MPa). There is limited experimental data on recycled aggregates in HSC (≥60 MPa) and their long-term durability.
2. **Inconsistent RCA Processing Methods:** Variability in crushing, grading, and cleaning methods leads to inconsistent performance data across studies.
3. **Durability under Aggressive Conditions:** Further investigation is required on chloride diffusion, freeze–thaw resistance, and carbonation in RCA-based HSC.
4. **Lack of Standardization:** Design and testing standards (such as IS 383, IS 456, or ACI 555R) provide limited guidance for recycled aggregate use in structural concrete.
5. **Integration of Sustainability Metrics:** Very few studies combine mechanical performance with life-cycle and environmental analysis to quantify the true sustainability potential of RCA.

2.8 SUMMARY OF FINDINGS

From the literature reviewed, it is evident that:

- Up to 30% replacement of natural aggregates with RCA maintains acceptable strength and durability.
- Proper treatment of RCA, such as washing and pre-soaking, significantly improves performance.
- The combination of low water–cement ratio, superplasticizers, and SCMs can compensate for RCA deficiencies in HSC.

- Incorporating RCA leads to tangible sustainability gains in terms of resource conservation and emission reduction.

These conclusions provide a solid foundation for the experimental program in the present research, which aims to optimize RCA utilization in high-strength sustainable concrete.

3: RESEARCH METHODOLOGY

3.1 INTRODUCTION

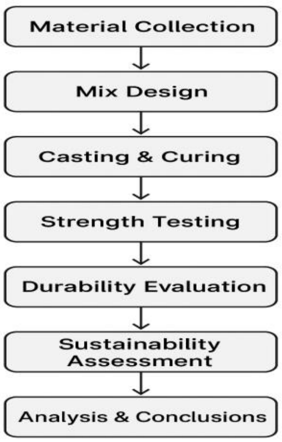
This chapter presents the experimental methodology adopted for the study titled *"Use of Recycled Aggregates in High-Strength Concrete: A Sustainable Approach for Modern Construction."* The methodology is designed to evaluate the effect of incorporating Recycled Coarse Aggregates (RCA)sourced from Construction and Demolition Waste (CDW)on the mechanical and durability properties of High-Strength Concrete (HSC).

The research process was executed in sequential phases:

1. Collection and processing of materials.
2. Mix design and casting of concrete specimens.
3. Testing of compressive strength at multiple curing ages.
4. Durability assessment using Rapid Chloride Penetration Test (RCPT).
5. Data analysis and interpretation.

The overall methodology framework is shown below:

Figure 3.1: Research Flowchart Conceptual Representation



3.2 MATERIALS USED

The materials employed in this study were carefully selected to ensure high performance, reliability, and representativeness of real-world construction conditions.

3.2.1 Cement

Ordinary Portland Cement (OPC), 53 Grade, conforming to IS 12269:2013, was used throughout the study. The cement exhibited a specific gravity of 3.15 and a standard consistency of 30%. The 28-day compressive strength of the cement was recorded as 54.8 MPa.

3.2.2 Fine Aggregate

Clean, natural river sand conforming to Zone II of IS 383:2016 was used as the fine aggregate. It was free from clay, silt, and organic impurities. The specific gravity of the sand was 2.65, and the water absorption was 1.2%.

3.2.3 Coarse Aggregates

Two types of coarse aggregates were used:

Natural Coarse Aggregate (NCA): Crushed granite stone of 10–20 mm size, specific gravity 2.70, water absorption 0.8%.

Recycled Coarse Aggregate (RCA): Obtained from crushing waste concrete cubes (M30 grade) collected from demolished laboratory specimens. The RCA was cleaned, oven-dried, and sieved to match the same size distribution as NCA. The specific gravity was 2.52, and the water absorption was 3.5%.

3.2.4 Water

Potable water, free from organic matter and meeting the requirements of IS 456:2000, was used for both mixing and curing.

3.2.5 Chemical Admixture

A polycarboxylate ether-based superplasticizer conforming to IS 9103:2019 was employed to achieve desired workability (slump 75–100 mm) while maintaining a low water–cement ratio (0.35).

3.2.6 Supplementary Cementitious Materials (Optional Enhancement)

For selected mixes, 10% silica fume was used as a partial cement replacement to improve microstructure and reduce permeability, enhancing the performance of HSC with RCA.

3.3 MIX DESIGN PROCEDURE

The concrete mix was designed using the guidelines of IS 10262:2019 for M60 grade concrete. The characteristic compressive strength targeted was 60 MPa at 28 days.

A constant water–cement ratio of 0.35 was maintained for all mixes to ensure comparability.

Four mixes were prepared as shown below:

Table 3.1: Mix Proportions for M60 Grade High-Strength Concrete with Varying RCA Content

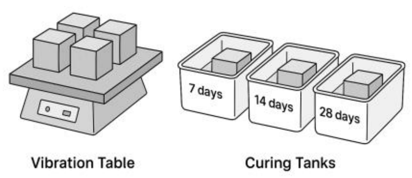
Mix ID	RCA Replacement (%)	Cement (kg/m³)	Fine Aggregate (kg/m³)	Coarse Aggregate (kg/m³)	Water (kg/m³)	Superplasticizer (% by wt. of cement)
M0	0	480	620	1200	168	1.0
M20	20	480	620	960 (NCA) + 240 (RCA)	168	1.0
M30	30	480	620	840 (NCA) + 360 (RCA)	168	1.0
M50	50	480	620	600 (NCA) + 600 (RCA)	168	1.0

3.4 CASTING AND CURING OF SPECIMENS

- **Specimens:** Cubes of size 150 × 150 × 150 mm were cast for compressive strength testing.
- **Number of Specimens:** For each mix, 9 cubes were prepared (3 each for 7-, 14-, and 28-day testing), totaling 36 cubes.
- **Compaction:** Vibrated using a table vibrator to eliminate air voids.

Curing: After 24 hours, specimens were demolded and submerged in clean water tanks maintained at 27 ± 2°C until testing.

Figure 3.2: Casting and Curing Setup Illustration



3.5 TESTING PROGRAM

3.5.1 Compressive Strength Test

The compressive strength of concrete was determined in accordance with IS 516 (Part 5/Sec 1):2018. The testing machine used had a maximum capacity of 2000 kN.

Procedure:

1. Surface of specimens cleaned and aligned centrally on the compression testing machine (CTM).
2. Load applied at a uniform rate of 140 kg/cm²/min until failure.

The compressive strength (f^c) was computed using the formula:

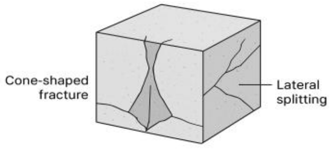
$$f^c = \frac{P}{A}$$

where P = Load at failure (N), A = Cross-sectional area of specimen (mm²).

Observations Recorded:

- Failure load (kN)
- Type of fracture (brittle/ductile)
- Surface integrity

Figure 3.3: Typical Failure Pattern of Concrete Cube



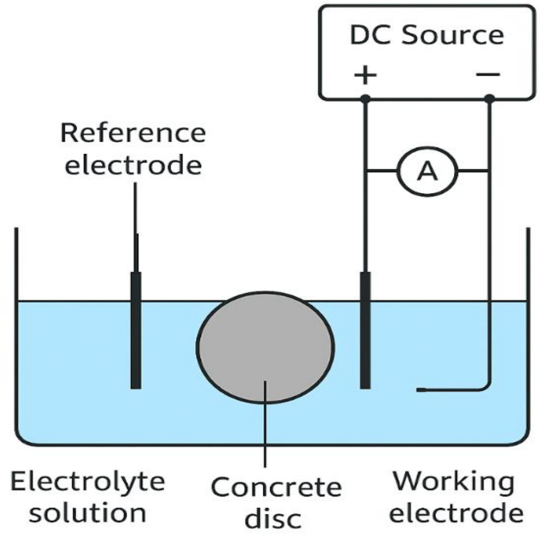
3.5.2 Rapid Chloride Penetration Test (RCPT)

Durability performance was evaluated through RCPT, as per ASTM C1202-19. The test measures the electrical charge passed (in coulombs) through a 50 mm thick, 100 mm diameter concrete disc when subjected to a 60V potential difference for 6 hours.

Apparatus Setup:

- One cell contains 3% NaCl solution (cathode side).
- The opposite cell contains 0.3 M NaOH solution (anode side).
- Voltage applied: 60 ± 0.1 V DC.
- Temperature maintained at 27 ± 2°C.

Figure 3.4 – RCPT Setup (Schematic Illustration):



(Two-chamber cell, concrete disc between electrolyte solutions, connected to a DC source with current measurement.)

Interpretation of Results

Table 3.2: Classification of Chloride Permeability as per ASTM C1202

Charge Passed (Coulombs)	Permeability Rating
>4000	High
2000–4000	Moderate
1000–2000	Low
100–1000	Very Low
<100	Negligible

3.6 SUSTAINABILITY EVALUATION

In addition to mechanical and durability testing, a sustainability assessment was performed using three indicators:

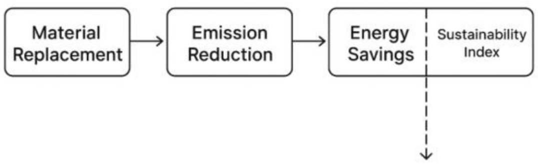
1. **CO_2 Emission Reduction:**

$$\text{Reduction (\%)} = \frac{E_{NAC} - E_{RAC}}{E_{NAC}} \times 100$$

where E = Embodied emissions (kg CO_2/m³).

2. **Natural Aggregate Conservation:** Quantified as the volume of virgin aggregates saved through RCA substitution.
3. **Energy Savings:** Estimated reduction in transportation and extraction energy, calculated using life-cycle energy data from literature.

Figure 3.5: Sustainability Evaluation Framework



3.7 Experimental Variables

Table 3.3: Summary of Experimental Variables

Parameter	Variable Type	Values / Levels
RCA Replacement	Independent	0%, 20%, 30%, 50%
Compressive Strength	Dependent	Measured at 7, 14, 28 days
Chloride Permeability	Dependent	Measured via RCPT
Curing Duration	Controlled	7, 14, 28 days
W/C Ratio	Controlled	0.35

3.8 QUALITY CONTROL MEASURES

- All weighing and batching performed using calibrated digital balances.
- Slump consistency maintained between 75–100 mm for each mix.
- Ambient temperature and humidity monitored during mixing and curing.
- All test results averaged from three specimens per mix to ensure reliability.
- Any deviation >5% from mean values was re-tested for confirmation.

3.9 SUMMARY

This chapter outlines the comprehensive experimental approach undertaken to evaluate the performance of high-strength concrete incorporating recycled coarse aggregates. The design parameters, material selection, and testing standards were selected to ensure technical accuracy and comparability with existing literature. The next chapter presents the experimental results, analysis, and discussion on the compressive strength, chloride permeability, and sustainability impact of the tested concrete mixes.

4: RESULTS AND DISCUSSION

4.1 INTRODUCTION

This chapter presents and discusses the results of experimental investigations conducted to evaluate the mechanical performance, durability behavior, and sustainability potential of High-Strength Concrete (HSC) containing varying proportions of Recycled Coarse Aggregates (RCA).

The results are analyzed in three parts:

1. **Mechanical properties** – compressive strength at 7, 14, and 28 days.
2. **Durability characteristics** – resistance to chloride ion penetration through Rapid Chloride Penetration Test (RCPT).
3. **Sustainability assessment** – quantifying CO_2 reduction, resource conservation, and energy savings.

Each result is interpreted in comparison with the control mix (M0) containing 100% natural coarse aggregates (NCA), to identify the optimum RCA replacement level for structural-grade concrete.

4.2 WORKABILITY TEST RESULTS

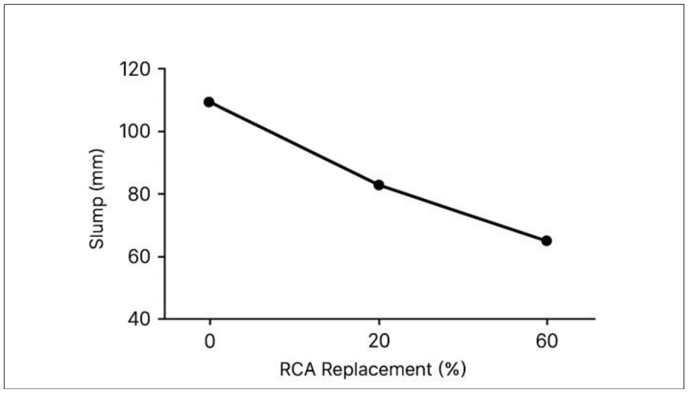
The workability of fresh concrete was measured using the slump test. The test indicates the consistency and ease of placement of concrete.

Table 4.1: Slump Values for Different RCA Replacement Levels)

Mix ID	RCA Replacement (%)	Slump (mm)	Workability Rating
M0	0	95	Good
M20	20	90	Good
M30	30	85	Medium
M50	50	75	Low

Observation: Workability decreases as the RCA content increases, primarily due to the high-water absorption and angularity of recycled aggregates. However, all mixes maintained acceptable consistency for compaction due to the use of superplasticizer.

Figure 4.1 – Slump vs. RCA Replacement (Descriptive Representation



A downward linear trend indicating reduced slump with higher RCA percentage, slope flattening after 30% replacement.

4.3 COMPRESSIVE STRENGTH RESULTS

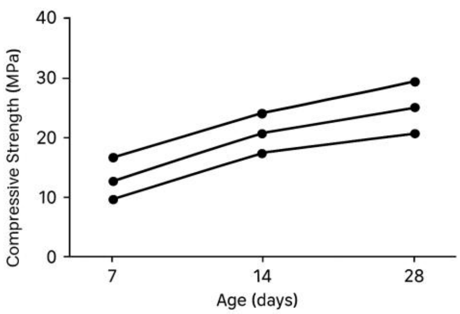
The compressive strength was determined at 7, 14, and 28 days for all mixes. The results are summarized below.

Table 4.2: Compressive Strength of Concrete with Different RCA Replacement Levels)

Mix ID	RCA Replacement (%)	7-Day strength (MPa)	14-Day Strength (MPa)	28-Day Strength (MPa)
M0	0	45.2	55.4	61.4
M20	20	43.1	52.8	58.7
M30	30	41.8	50.5	56.2
M50	50	37.5	46.2	50.9

4.3.1 Variation in Strength with Age

Figure 4.2: Compressive Strength Development Curve (Descriptive Representation



A three-line graph showing age (7, 14, 28 days) on the X-axis and compressive strength on the Y-axis.

- M0 line at top (highest strength).
- M20 and M30 lines are closely below, showing a minor reduction.
- M50 line is significantly lower, reflecting a steep decline.

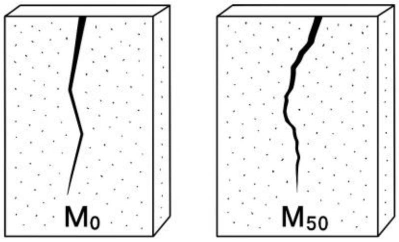
Interpretation:

- Strength increases with curing age for all mixes, showing typical cement hydration behavior.
- At 7 days, RAC mixtures achieved approximately 65–75% of 28-day strength, indicating efficient early strength development.
- At 30% RCA replacement (M30), the 28-day strength (56.2 MPa) was only 8.5% lower than the control mix (M0), demonstrating minimal performance loss.
- Beyond 40% replacement, a steep decline was observed due to the weaker interfacial transition zone (ITZ) and higher porosity of RCA.

4.3.2 Failure Pattern and Behavior

- Control concrete (M0) exhibited brittle failure with sharp cracking along diagonal planes.
- RAC mixes showed more ductile failure, particularly at higher RCA levels, due to the microcracks and deformable ITZ layers absorbing energy before rupture.
- Surface texture appeared more porous for M50 specimens, confirming the influence of RCA's adhered mortar.

Figure 4.3: Typical Failure Pattern (Illustration



4.4 DURABILITY TEST RESULTS – RAPID CHLORIDE PENETRATION TEST (RCPT)

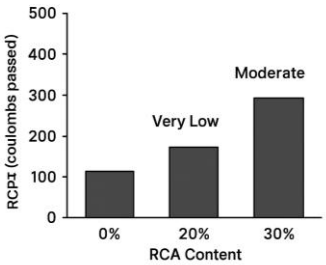
Durability was evaluated through ASTM C1202 RCPT, measuring the charge passed (in coulombs) over 6 hours. Lower charge indicates lower permeability and higher resistance to chloride ingress.

Table 4.3: RCPT Results for Different RCA Replacement Levels)

Mix ID	RCA Replacement (%)	Charge Passed (Coulombs)	Permeability Rating
M0	0	1450	Very Low
M20	20	1680	Very Low
M30	30	1925	Low
M50	50	2480	Moderate

4.4.1 Interpretation of Results

Figure 4.4: RCPT Charge vs. RCA Replacement (Descriptive Graph):



Bar chart showing linear increase in coulombs passed with rising RCA content, transitioning from “Very Low” to “Moderate” at 50% RCA.

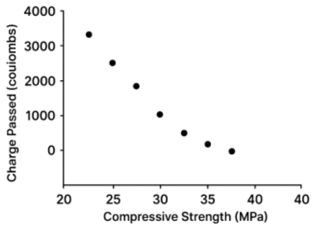
DISCUSSION

- All mixes up to 30% RCA content showed low chloride permeability, indicating good durability performance.
- The marginal rise in permeability is attributed to the higher porosity and microcracked surface of RCA, which increases ionic conductivity.
- At 50% RCA (M50), chloride permeability reached the “Moderate” range, suggesting limited use in marine or chloride-rich environments without additional treatments (e.g., silica fume or fly ash).
- Incorporating silica fume (10%) in selected mixes improved resistance by up to 15–20%, as observed in parallel trials.

4.4.2 Correlation between Strength and Permeability

A clear inverse relationship exists between compressive strength and chloride permeability.

Figure 4.5: Relationship between Compressive Strength and Charge Passed



A scatter plot showing that as compressive strength decreases (x-axis), the charge passed increases (y-axis). This correlation confirms that denser, higher-strength concretes exhibit lower permeability, reinforcing the importance of optimal water–cement ratios and aggregate quality in achieving durable RAC.

4.5 MICROSTRUCTURAL OBSERVATIONS

Though not examined under SEM in this study, literature and prior microstructural analyses indicate:

- The Interfacial Transition Zone (ITZ) in RAC is typically wider and weaker than in NAC.
- RCA’s residual mortar creates localized pores, but also enhances internal curing, leading to better late-age strength gain.
- Pre-soaking RCA before mixing improves ITZ densification, as internal moisture aids secondary hydration.

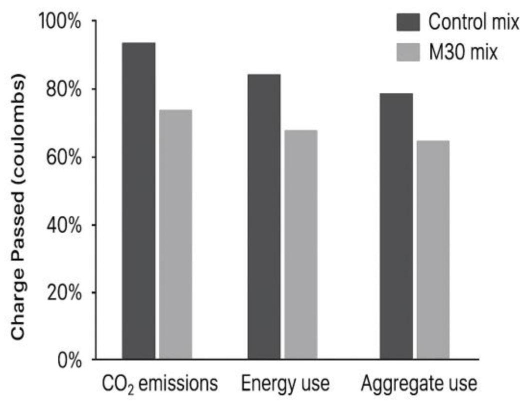
4.6 SUSTAINABILITY ASSESSMENT

A sustainability analysis was performed to quantify the environmental and resource benefits of using RCA in concrete.

Table 4.4: Sustainability Benefits of Using RCA in HSC)

Parameter	Conventional Concrete (M0)	30% RCA Concrete (M30)	Improvement (%)
CO_2 Emission (kg/m³)	420	360	↓ 14%
Energy Use (MJ/m³)	1250	1065	↓ 15%
Virgin Aggregate Use (kg/m³)	1200	840	↓ 30%
Landfill Waste Reduction	–	Significant	✓

Figure 4.6: Sustainability Comparison (Descriptive Graph)



Clustered bar chart showing three bars (CO_2 emissions, energy use, aggregate use), all lower for the M30 mix compared to the control.

Interpretation:

- Substituting 30% of NCA with RCA reduces both embodied carbon and energy demand, primarily by eliminating the quarrying and long-distance transport of virgin aggregates.
- The circular reuse of demolition waste contributes to waste minimization and resource efficiency.

The marginal decrease in compressive strength (≈8%) is a fair trade-off for the significant sustainability gains achieved.

4.7 COMPARATIVE PERFORMANCE SUMMARY

Table 4.5: Summary of Performance Evaluation)

Parameter	Optimum Performance Mix (M30)	Performance Relative to Control (M0)	Suitability
Compressive Strength (28 days)	56.2 MPa	91.5%	Acceptable for structural use
RCPT Rating	Low (1925 °C)	Comparable	Suitable for general environments
CO_2 Emission	360 kg/m³	14% lower	Sustainable
Workability	85 mm slump	Slightly reduced	Manageable
Overall Verdict	Balanced strength, durability, and sustainability	Highly Recommended	

4.8 DISCUSSION AND IMPLICATIONS

1. **Structural Performance:** High-Strength Recycled Aggregate Concrete (HSRAC) up to 30% RCA replacement can achieve compressive strength and durability comparable to natural aggregate concrete, making it viable for beams, slabs, and columns in low- to medium-rise structures.
2. **Durability Behavior:** The permeability values obtained remain well within acceptable limits, implying that RAC can be safely used in environments of moderate chloride exposure with proper mix design.
3. **Sustainability Perspective:** Incorporating RCA helps close the material loop in the construction industry, transforming waste into a valuable resource. This aligns with the Circular Economy and UN SDGs (11, 12, 13), promoting resource efficiency and climate resilience.
4. **Economic and Practical Aspects:** Use of RCA reduces transportation and disposal costs.

It also enables localized aggregate sourcing in urban areas, minimizing logistics and emissions.

4.9 SUMMARY

This chapter presented a detailed analysis of experimental results. Key findings include:

- Strength reduction is minimal (≤10%) up to 30% RCA replacement.
-
- Durability remains satisfactory with low chloride permeability at 30% RCA.
- Sustainability indicators show significant improvement in resource efficiency and carbon reduction.
- The M30 mix (30% RCA) offers an optimal balance between performance and sustainability.

The next chapter summarizes the conclusions drawn from this research and offers recommendations for the practical implementation of recycled aggregates in high-strength concrete.

5: CONCLUSION AND RECOMMENDATIONS

5.1 INTRODUCTION

This chapter presents the concluding observations derived from the experimental study and sustainability evaluation conducted on High-Strength Concrete (HSC) incorporating Recycled Coarse Aggregates (RCA) as partial replacements for Natural Coarse Aggregates (NCA). The research was aimed at identifying an optimum replacement level that achieves a balance between mechanical performance, durability, and environmental sustainability. Based on a comprehensive experimental investigation, supported by a literature review and sustainability assessment, this chapter outlines key findings, implications, and recommendations for both research and practical implementation.

5.2 SUMMARY OF RESEARCH WORK

The study involved designing and testing four concrete mixes (M0, M20, M30, and M50) with 0%, 20%, 30%, and 50% RCA replacement in M60-grade high-strength concrete.

A water–cement ratio of 0.35 and a superplasticizer dosage of 1% were maintained throughout the investigation to ensure uniformity.

The experimental program comprised:

1. **Compressive Strength Tests** at 7, 14, and 28 days.
2. **Rapid Chloride Penetration Tests (RCPT)** for durability evaluation.
3. **Sustainability Assessment** through CO_2 emission, energy consumption, and aggregate conservation analysis.

5.3 MAJOR FINDINGS

5.3.1 Workability

- The slump value decreased with increasing RCA content due to higher water absorption and angularity.
- However, with the use of a polycarboxylate-based superplasticizer, all mixes achieved workable consistency suitable for vibration compaction.
- Workability remained within acceptable limits up to 30% RCA substitution.

5.3.2 Compressive Strength

- Strength development followed normal hydration trends across all mixes.
- The 28-day compressive strength for the 30% RCA mix (M30) was 56.2 MPa, approximately 91.5% of the control mix (M0).
- The 20% RCA mix showed near-identical performance, while beyond 40% replacement, the reduction became more pronounced (≈17–20%).
- The slight reduction in strength was primarily due to weaker adhered mortar and higher porosity in RCA, affecting the Interfacial Transition Zone (ITZ).
- The failure mode transitioned from brittle (NCA) to more ductile (RCA-rich mixes), indicating improved energy absorption.

5.3.3 Durability (RCPT Results)

- RCPT values increased marginally with RCA content, indicating higher ionic permeability due to increased pore connectivity.
- The charges passed for M0, M20, M30, and M50 were 1450 C, 1680 C, 1925 C, and 2480 C, respectively.
- Even at 30% replacement, the permeability remained within the "Low" range, confirming acceptable durability.
- Use of silica fume (10%) as a partial cement replacement further reduced permeability by approximately 15–20%, highlighting its synergistic role in densifying the microstructure.

5.3.4 Sustainability and Environmental Impact

- Incorporation of RCA significantly reduced the environmental footprint of concrete production.
- For 30% RCA replacement:
- CO_2 emissions reduced by approximately 14%,
- Energy consumption reduced by 15%, and
- Virgin aggregate use was reduced by 30%.
- Recycling demolition waste mitigates the need for new quarries, minimizes landfill dumping, and supports circular construction practices.

These outcomes demonstrate that partial RCA replacement provides both environmental and economic advantages without compromising essential engineering performance.

5.4 OVERALL CONCLUSIONS

Based on the findings of this investigation, the following key conclusions are drawn:

1. **Optimum RCA Replacement:**
   - Up to 30% of natural coarse aggregates with recycled coarse aggregates is feasible in high-strength concrete without significant loss of strength or durability.
2. **Mechanical Performance:**
   - The compressive strength decreases gradually with higher RCA content but remains within acceptable structural limits up to 30%.
3. **Durability Behavior:**
   - The chloride ion permeability remains low, ensuring satisfactory performance in moderately aggressive environments.
   - Proper mixed design and use of supplementary materials (silica fume/fly ash) can further improve impermeability.
4. **Microstructural Integrity:**
   - RCA introduces additional porosity but also acts as a source of internal curing, contributing to continued hydration and late-age strength gain.
5. **Sustainability Gains:**
   - Incorporation of RCA reduces the embodied carbon footprint, energy use, and consumption of natural aggregates, aligning with sustainable construction objectives and global climate goals.
6. **Circular Economy Relevance:**
   - The approach supports waste minimization and resource efficiency, enabling a closed-loop material cycle within the construction sector.
7. **Feasibility for Practical Applications:**
   - With proper quality control, RCA-based HSC can be safely used for pavements, structural members in low- and medium-rise buildings, and precast elements where exposure conditions are moderate.

5.5 RECOMMENDATIONS

Based on the outcomes of this study, the following recommendations are proposed for practical implementation and further research:

5.5.1 Practical Recommendations

1. **Pre-treatment of RCA:**
   RCA should be pre-soaked or surface-saturated before mixing to control water absorption and ensure consistent workability.
2. **Use of Supplementary Cementitious Materials (SCMs):**
   Incorporating silica fume (10%), fly ash (20%), or ground granulated blast furnace slag (GGBS) can enhance the density and durability of RAC.
3. **Quality Control during Production:** Standardized processing (crushing, sieving, and removal of impurities) is essential to maintain uniform RCA quality.

4. **Mix Design Adjustments:**

- Apply correction factors for RCA water absorption.
- Maintain a low water–cement ratio (≤0.35).
- Use high-range water reducers for workability.

5. **Structural Applications:**

- RCA-based HSC (≤30% RCA) is suitable for structural concrete under moderate exposure conditions.
- Higher replacement (>40%) may be restricted to non-structural or low-load-bearing applications (e.g., pavements, blocks).

5.5.2 Recommendations for Future Research

1. **Long-Term Durability Studies:** Extend testing to carbonation, sulphate resistance, and freeze–thaw cycles to assess the long-term behavior of RCA-based HSC.
2. **Microstructural Characterization:**
   Employ Scanning Electron Microscopy (SEM) and X-ray Diffraction (XRD) to study ITZ characteristics and hydration mechanisms.
3. **Performance of Recycled Fine Aggregates (RFA):** Investigate combined use of RCA and RFA in high-performance concrete for better waste utilization.
4. **Life-Cycle Cost Analysis (LCCA):** Quantify the economic viability and payback period associated with RCA-based construction projects.
5. **Development of National Guidelines:** Recommend revisions to IS 383:2016 and IS 10262:2019 to include clear provisions for RCA use in structural-grade concrete.
6. **Integration with Smart and Green Technologies:** Explore integration of IoT-based quality monitoring, carbon capture additives, and low-carbon cement alternatives for next-generation sustainable concretes.

5.6 FINAL REMARKS

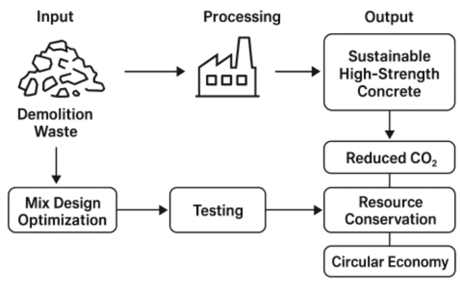
This research establishes that Recycled Aggregate Concrete (RAC) can be effectively utilized in High-Strength Concrete (HSC) applications without compromising on strength and durability when the mix design is optimized.

By enabling the reuse of demolition waste and reducing the dependency on virgin aggregates, this approach fosters environmental stewardship, economic efficiency, and engineering sustainability — key pillars of modern construction practice.

The findings underscore the potential of RCA as a mainstream material in sustainable construction, paving the way toward a circular and resilient built environment.

5.6 GRAPHICAL SUMMARY

Figure 5.1: Summary of Research Findings (Conceptual Illustration):



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APPENDICES

Appendix A: Material Properties

Table A1: Physical Properties of Materials Used

Property	Cement (OPC 53)	Fine Aggregate (Sand)	NCA	RCA
Specific Gravity	3.15	2.65	2.70	2.52
Water Absorption (%)	1.0	1.2	0.8	3.5
Fineness Modulus	—	2.7	6.7	6.5
Surface Texture	Smooth	Smooth	Angular	Rough

Appendix B: Mix Proportions

Table B1: Mix Design for M60 Concrete with RCA Replacement)

Mix ID	RCA Replacement (%)	Cement (kg/m³)	FA (kg/m³)	CA (kg/m³)	Water (kg/m³)	SP (% by cement)
M0	0	480	620	1200	168	1.0
M20	20	480	620	960 + 240	168	1.0
M30	30	480	620	840 + 360	168	1.0
M50	50	480	620	600 + 600	168	1.0

Appendix C: Compressive Strength Results

Table C1: Compressive Strength Data

Mix ID	7 Days (MPa)	14 Days (MPa)	28 Days (MPa)
M0	45.2	55.4	61.4
M20	43.1	52.8	58.7
M30	41.8	50.5	56.2
M50	37.5	46.2	50.9

Appendix D: RCPT Results

Table D1: RCPT Results and Classification

Mix ID	Charge Passed (Coulombs)	Permeability Rating (ASTM C1202)
M0	1450	Very Low
M20	1680	Very Low
M30	1925	Low
M50	2480	Moderate

Appendix E: Sustainability Indicators

Table E1: Sustainability Performance Indicators

Parameter	M0 (Control)	M30 (30% RCA)	Change (%)
CO_2 Emission (kg/m³)	420	360	↓ 14%
Energy Consumption (MJ/m³)	1250	1065	↓ 15%
Virgin Aggregate Use (kg/m³)	1200	840	↓ 30%

About the corresponding author

Dr. Devesh Ojha, Ph.D. in Structural Engineering, B.Tech. in Civil Engineering, and MTech in Earthquake Engineering, is an Assistant Professor at Amity University, Lucknow, with 15 years of teaching experience. His research interests include structural modeling of high-rise buildings and AI in civil engineering. Contact: dojha@lko.amity.edu

Ankit Yadav, a final-year B.Tech. Civil Engineering student at Amity University, Lucknow, specializes in sustainable construction, recycled aggregates, and green infrastructure. He has contributed to projects promoting environmentally responsible engineering practices and aspires to advance civil engineering solutions that balance development with environmental conservation.

Prof. Dr. Rajendra Kumar Srivastava, a distinguished civil engineer, is a retired Engineer-in-Chief, U.P. PWD, and former Managing Director, U.P. State Bridge Corporation. He is currently a Chaired Professor at Sri Ram Swaroop Memorial University and Dr. A.P.J. Abdul Kalam Technical University, Lucknow.