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Original Article

Innovative Concrete Mix Design Incorporating Recycled Aggregates: Bridging IS Code 10262:2019 with Sustainable Construction Practices

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Abstract *- This study investigates the integration of recycled aggregates into concrete mix designs while adhering to the guidelines established by the Indian Standard Code 10262:2019. The research addresses the growing challenge of construction and demolition waste management through sustainable concrete production practices. Recycled Concrete Aggregates (RCA) were incorporated at varying replacement percentages (20%, 40%, and 60%) of natural aggregates in concrete mixtures designed for M25 and M30 grade concrete. The experimental program evaluated these mixes' Plastic stage and Matured properties, including workability, Hardened strength, split tensile strength, and durability characteristics. Results indicate that up to 30% of replacement levels maintained adequate mechanical properties while demonstrating measurable environmental benefits. A modified mix design methodology compatible with IS 10262:2019 was developed to account for the higher water absorption of recycled aggregates and to establish grade identification for RCA materials used in concrete. Life cycle assessment revealed a significant reduction of natural resource depletion with the mix of recycled aggregates. This research provides a practical path for implementing recycled aggregate concrete within the framework of Indian construction standards, bridging the gap between conventional practice and sustainable construction techniques. The findings support the viability of recycled aggregates as an environmentally responsible alternative in structural concrete applications while maintaining compliance with existing design codes.*

Keywords *- Recycled Concrete Aggregates (RCA), IS Code 10262:2019, Sustainable construction, Waste management, Concrete mix design, Compressive strength, Durability, Construction and demolition waste.*

1. Introduction

The global construction industry faces unprecedented challenges in resource management and environmental sustainability. As urban development accelerates, the demand for concrete, the world's most consumed manufactured material after water, rises exponentially. This growing demand has led to critical concerns regarding the depletion of natural aggregates and the environmental impact of concrete production. Despite numerous studies on Recycled Aggregate Concrete (RAC), a significant research gap exists in systematically integrating recycled aggregates with current Indian regulatory frameworks, particularly the recently updated IS Code 10262:2019. India's construction sector, projected to grow 7.1% annually through 2025, faces particular urgency in addressing these sustainability challenges. Implementing IS Code 10262:2019, which updated concrete mix design procedures, provides a regulatory framework that can potentially accommodate innovative solutions such as recycled aggregate concrete. However, while international studies have extensively investigated RAC properties, there is limited research on how these materials perform within IS Code 10262:2019 specifications. Previous studies by (Silva et al., 2014) and (Tam et al., 2018) demonstrated RAC feasibility internationally, but their findings cannot be directly applied to Indian conditions due to different regulatory requirements and material properties. Current literature lacks a comprehensive framework for implementing RAC within IS Code 10262:2019, and Indian standards have no specific grade designations for concrete containing recycled aggregates. This study addresses these gaps by being the first to systematically integrate RAC technologies with IS Code 10262:2019 (Standard, 2019) and introduces novel RCA grades (M25, M30) where the asterisk indicates RCA inclusion a classification system not addressed in current standards. This research aims to bridge this critical gap by developing innovative concrete mix designs incorporating recycled aggregates while adhering to the IS Code

10262:2019 guidelines. The IS Code has established the standard grade identification of concrete, such as M10, M20, and M25.

However, no explicit provision exists for distinct grade identification in such mixes when incorporating RCA (Recycled Concrete Aggregates) in replacement or addition forms, whether coarse or fine aggregates. Consequently, this study proposes introducing specific RCA grades, such as M25* or M30*, where the asterisk indicates the inclusion of RCA materials. This provision will address the absence of clear guidelines for RCA utilization, which has hindered its adoption in fresh construction projects. Using recycled concrete aggregates presents significant opportunities for reducing the environmental footprint of construction projects. These materials, derived from Construction and Demolition (C&D) waste, offer a dual benefit: diverting waste from landfills while reducing the extraction of virgin materials. Recent studies suggest properly processed recycled aggregates can replace up to 30% of natural aggregates in structural concrete without significant performance deterioration. However, the challenge lies in establishing standardized procedures that ensure sustainability and structural integrity within existing regulatory frameworks. To ensure the successful implementation of RCA in concrete mix designs, this research synthesizes advanced material characterization techniques, mix design optimization methodologies, and performance evaluation frameworks tailored explicitly to Indian conditions and standards. The resulting concrete formulations aim to meet both sustainability objectives and engineering requirements. By systematically investigating the properties of recycled aggregates and their interaction with cementitious materials, this study establishes practical guidelines for sustainable concrete production that align with current Indian regulatory standards. The findings from this research hold significant implications for construction stakeholders, from policymakers to engineers and contractors. By offering the first comprehensive roadmap for implementing sustainable concrete technologies within the IS Code 10262:2019 framework, this study represents an essential step toward reconciling the construction industry's resource demands with global sustainability imperatives while maintaining structural performance and regulatory compliance.

2. Literature Review

2.1. Overview of Sustainable Construction

The construction industry consumes vast quantities of natural resources while generating substantial amounts of waste. Sustainable construction practices, such as incorporating RCA in concrete mix design, are essential for reducing environmental impact and fostering a circular economy (Xiao et al., 2022). Implementing innovative concrete mix designs that incorporate recycled aggregates can help align construction practices with IS Code 10262:2019, the Indian Standard for concrete mix proportioning, while promoting sustainability. The construction industry's substantial environmental impact necessitates sustainable practices that promote "circular economy principles (Pacheco-Torgal et al., 2021) (Pacheco & de Brito, 2021) 'Recycled Concrete Aggregate (RCA) derived from construction and demolition waste' offer promising alternatives to natural aggregate. Contributing to environmental preservation and resource conservation (H. S. Joseph et al., 2023) 'Concrete production accounts for approximately 8% of global carbon emissions, underscoring the critical need for innovative low-carbon alternatives to support sustainable construction, with researchers seeking sustainable materials for eco-friendly cement and concrete to reduce CO2 emissions and The energy-intensive nature of traditional concrete production has prompted extensive research into low-carbon concrete technology, with emerging solutions including 'supplementary cementitious materials, alkali-activated and geopolymer concrete, and carbon capture and utilization showing potential to reduce emissions by up to 30-50%, (Cheng et al., 2023) comprehensive review address the growing environmental concerns 'related to Construction and Demolition (C&D) waste , highlighting that more than 3.57 billion tons of C&D, waste are produced annually worldwide , with recycling playing a significant role in addressing, environmental concerns and promoting sustainable construction practice and circular economy principles. (Patil et al., 2024) 'construction industry development has led to the generation of Construction and Demolition Waste (CWD), imposing significant pressure on ecology and the environment, with the study discussing current research on recycled coarse or fine aggregate, focusing on the physical, mechanical and durability properties of sustainable concrete (Luo et al., 2024)

2.2. International Standards and Guidelines

Several countries have established guidelines for RCA implementation. The European Standard EN 12620 provides specifications for recycled aggregates, while the American Concrete Institute (ACI 555R-01) offers design guidelines for recycled aggregate concrete (Thompson et al., 2023). These international standards emphasize source material quality and rigorous testing protocols for successful RCA implementation.

2.3. Characteristics of Recycled Aggregate

Integrating recycled aggregate into concrete mixes offers a viable solution for reducing dependence on virgin material while minimizing waste disposal, though incorporating RCA can reduce compressive strength by up to 25% in high-strength concrete applications. (Jagadesh et al., 2024) (Skocek et al., 2024) 'Recycled aggregates from C&D waste demonstrate potential for concrete production with replacement level typically maintained under 30% to minimize performance reduction. While contributing to circular economy principles by reducing landfill disposal by approximately 4.5 billion tons annually research analysis of 1580 documents between 2013-2022 shows that recycled concrete aggregate achieves mechanical properties within 85-95% of natural aggregate (Pacheco & de Brito, 2021) Implementation of recycled aggregate in concrete mixture shows strength reduction of 10-20% at 50% replacement levels, while environmental benefits include 30-4% reduction in Co_2 emission and 60-70% reduction in natural resources consumption compared to conventional concrete production. (Kryeziu et al., 2023) Experimental study examine recycled coarse aggregate replacement ratio from 0% to 100% in 11 different concrete compositions finding that the maximum decrease in compressive flexural and tensile strength reached 19.4% ,18.3% and 19.6% respectively compared to control sample at 28 days (Qasim et al., 2024) Research evaluated the environmental and economic benefit of using recycled coarse aggregate from concrete block waste in 1 m^3 concrete sample, demonstrating that 50% replacement of natural coarse aggregate with recycled alternatives resulted in an average decrease of 3.30% in environmental impact (Los Santos-Ortega et al., 2024) The water absorption rate of recycled coarse aggregate obtained from crushed mortar with water cement ratio of 0.3 to 0.4 and 0.5 were 10.5% ,12.6% and 13.9% respectively , which decrease to 8.9% 9.9% and 7.6% after 10 days carbonation treatment , indicating that higher water absorption recycled aggregate benefit more from carbonation with reduction rate of 20.2% 24.1% (Jagadesh et al., 2024) The fraction of adhered mortar by volume decrease with increasing size of recycled concrete aggregate , with crushing process producing recycled concrete fines containing mainly hydrated cement past and sand ,where the boundary between RCA and RCF is typically set at 4mm particle size (Feng et al., 2023) Water absorption range of recycled fine aggregate varies from 4.3% to 13.1% while density varies from 1.91 to 2.56 g/cm^3, with addition of supplementary material like silica fume , fly ash, polycarboxylate either significantly mitigating negative effects by enhancing compressive strength approximately compared with control mixes without addtitatives (Jagadesh et al., 2024) The research utilized 32 concrete sample across four distinct group , establishing statically significant results for sustainable construction application the lifecycle assessment approach covering three phase (A1-A3) demonstrate quantifiable environmental benefit with specific focus on the cradle to gate impact assessment methodology for $1m^3$ of concrete production (Younes et al., 2024) The research utilized 32 concrete sample across four distinct group , establishing statically significant results for sustainable construction application the lifecycle assessment approach covering three phase (A1-A3) demonstrate quantifiable environmental benefit with specific focus on the cradle to gate impact assessment methodology for $1m^3$ of concrete production (Younes et al., 2024) “The optimum replacement of river sand by RFA in concrete was 30% (RFA30) The reduction in shrinkage and porosity were in order of 14% and 25% respectively’ (Bu et al., 2022) MRA have a high dispersion as data are distributed ‘range from 4% to 15% and 50% of them vary between about 4% and 8% on the contrary’ RCAs shows a clear lower dispersion having 50% of the data concentrated around the median value of 5% for these three w/c values the decrease of compressive strength for concrete made with RACs is about 10% (average value) while for MRAs it varies from 10 to 20% (Piccinali et al., 2022) chloride content at specific depths increase systematically with erosion age across different exposure condition, with concrete exposed to drying wetting cycles showing accelerated chloride penetration rates up to 25% higher than static immersion condition (Qu et al., 2022) Innovative study demonstrate that Nano-silica slurry pre-coating of recycled concrete aggregates significantly improves interfacial transition zone properties, with mercury intrusion porosimetry result confirming reduced porosity in the matrix near modified aggregates. The research shows that nano silica particles (0-20nm) provide nucleation sites for cement hydration, resulting in enhanced mechanical properties and reduced chloride ion penetration through improved pore structure refinement (Shan & Yu, 2022)

2.4. Performance Comparison RCVs Traditional Concrete

Comparative studies demonstrate that RCA concrete can achieve 85-95% of conventional concrete strength at 28 days when replacement levels are limited to 30% (Marvila et al., 2022) The addition of supplementary materials like silica fume, fly ash, and polycarboxylate ether significantly mitigated these adverse effects, enhancing the compressive strength by approximately 15-20% compared with control mix without additives (Singh et al., 2024) Recycled aggregates exhibit significantly higher water absorption rates compared to natural aggregates with typical values ranging from 2% to 10% for recycled aggregates versus 0.5% to 1.8% for natural aggregates (Ding et al., 2023) The higher absorption capacity of recycled aggregate necessitates accurate measurement of its saturated-surface dried water absorption. This primarily affects the adequate water-to-binder ratio of recycled aggregate concrete, with values typically ranging from 5% to 15% for recycled aggregates in China. The total aggregate demand reached 17.89 billion tons in 2021, highlighting the critical need for recycled aggregate solutions to balance environmental protection with construction demand (Duan et al., 2022). Recycled aggregates exhibit significantly higher water absorption rates than natural aggregates in the wetting procedure, where water consumption is typically 70% of the water absorption rate of the recycled aggregate to maintain similar slump values.

Water cement ratio adjustment in recycled concrete demonstrates that increasing the ratio from 0.29 to 0.37 results in 28 days of compressive strength and flexural tensile strength decrease of 17.89& 14.7%, respectively (Kashkash et al., 2023)

Table 1. Comparative Performance of RCA and Natural Aggregate Concrete

Property	Natural Aggregate Concrete	RCA Concrete (30% replacement)	Reference
Compressive Strength (MPa)	35-40	30-36	(Qasim et al., 2024)
Flexural Strength (MPa)	4.2-4.8	3.8-4.3	(Marvila et al., 2022)
Chloride Penetration (mm)	15-20	18-25	(Li et al., 2024)
Water Absorption (%)	3-5	5-8	(Duan et al., 2022)

2.5. Properties of Recycled Aggregates

Recycled Aggregates (RAs) possess distinct properties influencing their performance in concrete applications. Studies indicate that RAs typically exhibit higher water absorption rates than natural aggregates due to their porous nature, and concrete mixes incorporating RAs may require adjustments in water content to maintain desired workability and strength.

Additionally, RAs generally have a lower density compared to natural aggregates. The following table shows the Properties of Recycled aggregate.

Table 2. Properties of aggregate

Property	Findings	Reference
Density	7-15% lower than natural aggregates ranges from 2200-2400 kg/m³	(Meng et al., 2021)
Water Absorption	3-5 times higher (5-15%) significantly impacts workability	(Duan et al., 2022)
Los Angeles Abrasion	20-45% higher loss values indicate lower mechanical strength	(Kashkash et al., 2023)
Crushing Value	Typically, 25-35%, compared to 15-25% for natural aggregates	(Ding et al., 2023)
Adhered Mortar	Constitutes 25-45% of recycled aggregates by volume	(Feng et al., 2023)

2.6. Environmental Benefits and Successful Applications

The environmental impact of concrete that incorporated slag aggregate as the fine aggregate or bottom ash aggregate as the coarse aggregates was lower than that of concrete that incorporated natural aggregate when used to replace 30% of the fine and coarse aggregates in concrete with a design strength of 24 Mpa (Roh et al., 2020) The partial substitution of cement with SCMs and the use of recycled aggregates show visible and cost-effective benefits to the technical, environmental, and economic behaviour of the concrete industry. (Kong, 2022) The analysis showed that using geopolymer concrete in place of OPC concrete can reduce global warming potential by up to 53.7%, and the use of geopolymer concrete represents the reduction of acidification potential and photochemical oxidant formation in the impact categories. (Imtiaz et al., 2021) Results showed that the inclusion of steel fibres led to an increase in the global warming potential, whereas mixes with cement replacement by fly ash, slag, or microsilica recorded a reduction in GWP when recycled aggregates were used to replace natural aggregates in concrete production (Alzard et al., 2021)

2.7. Quality Control and Testing Requirements

The study established empirical relationships between destructive and non-destructive testing methods for concrete properties, providing practical assessment tools for quality control of RCA concrete systems (Minhaj et al., 2019) The study highlighted significant inconsistencies in material handling and quality control across different regions, with recycling rates for construction and demolition waste ranging from 30% to 90% across European Union member states, demonstrating the urgent need for systematic data collection enabling automated (Prasittisopin et al., 2025) This approach transforms construction demolition waste into valuable resources, contributing to environmental sustainability while maintaining concrete performance standards.

The practical implications include 15-25% cost savings and reduced carbon emissions of 15-20% in construction projects. The literature review demonstrates that Recycled Aggregate Concrete (RAC) has evolved from a post-war necessity in Europe to a systematically researched and increasingly standardized construction material worldwide. The development trajectory spans over seven decades, with a significant acceleration in research and implementation since 2010, particularly in the Indian context.

The field has progressed through three distinct phases: initial characterization and feasibility studies (2010-2014), treatment technique development and quality enhancement (2015-2019), and current optimization and standardization efforts (2020 onwards). The inclusion of RAC provisions in IS Code 10262:2019 represents a crucial regulatory milestone that has facilitated broader industry acceptance and commercial implementation.

Current research indicates that RAC technology has matured sufficiently for broader adoption, with international best practices providing frameworks for implementation in developing countries.

Table 3. Provision of IS Code 10262:2019

Aspect	Current Provision	Limitation	Reference Studies
Replacement Level	Limited to 30% replacement for structural concrete	Restrictive: research shows higher percentages are viable with proper quality control	(Marvila et al., 2022)
Water Adjustment	5% increase in water content for every 10% RCA	It does not account for variability in RCA quality	(Jagadesh et al., 2024)
Durability Considerations	Limited provisions for exposure condition	Inadequate guidance for aggressive environments	(Luo et al., 2024)
Quality Specifications	Basic requirements for crushed concrete as per IS 383	Lacks a comprehensive classification system for different RCA sources	(Bolan et al., 2024)

3. Existing Mix Design Methodologies

The adaptation of conventional mix design methodologies for recycled aggregate concrete has evolved significantly over the past decade, with researchers proposing various approaches to account for the unique properties of recycled aggregates. The modified versions of established methods in IS 10262:2019 have been widely adopted for practical applications.

3.1. Critical Evaluation of IS Code 10262:2019 Provisions

The revision of IS Code 10262 in 2019 marked a significant step forward in standardizing recycled aggregate concrete in India, introducing specific provisions for incorporating recycled aggregates in concrete mix design. While this represents progress, a critical evaluation reveals strengths and limitations in the current framework.

4. Proposed Framework for RCA Grade Identification and Mix Design

4.1. IS Code 10262:2019 and Concrete Mix Proportioning

The IS 10262:2019 standard outlines detailed guidelines for designing concrete mixes to achieve desired strength and workability. Key steps include determining the target mean strength, selecting an appropriate water-cement ratio, estimating water and cement content, and adjusting aggregate proportions. The use of RAs presents additional challenges in this context. The higher water absorption rate of RAs necessitates careful water content monitoring to ensure mix stability and durability. Researchers have explored several innovative strategies to optimize concrete mixes with RAs. These include:

4.1.1. Grade Identification

Design proper grade notation like M25*, and M30* with specific specifications

4.1.2. Water Content Adjustment

Increasing water content to compensate for RA's higher absorption while simultaneously controlling the water-cement ratio to maintain strength

4.1.3. Cement Content Adjustment

Increasing cement content to offset strength reduction; however, this must be balanced against cost and environmental considerations.

4.1.4. Aggregate Proportion Adjustment

Combining natural and recycled aggregates to improve packing density and workability.

4.2. Proposed RCA Grade Identification System

This research proposes a comprehensive grading system for recycled aggregate concrete that addresses the current gaps in IS 10262:2019. The proposed system introduces the "*" notation to identify concrete mixes containing recycled aggregates, with additional numerical indicators to specify replacement percentages and quality class.

Table 4. Proposed RCA Grade Identification System

Grade Designation	Description	Example
M25*	Standard concrete grade with recycled aggregates (unspecified percentage)	M25*
M25*-R30	Concrete with 30% recycled coarse aggregate replacement	M25*-R30
M25*-RF20	Concrete with 20% recycled fine aggregate replacement	M25*-RF20
M25*-R40-Q1	Concrete with 40% high-quality (Q1) recycled aggregate	M25*-R40-Q1

The quality classification (Q1, Q2, and Q3) is based on the key physical properties of recycled aggregates.

Table 5. Proposed Quality Classification for Recycled Aggregates

Property	Q1 (High Quality)	Q2 (Medium Quality)	Q3 (Low Quality)
Water Absorption (%)	<6	6-9	>9
Density (kg/m³)	>2400	2200-2400	<2200
Crushing Value (%)	<25	25-30	>30
Maximum replacement (%)	Up to 100	Up to 50	Up to 30

4.3. Modified Mix Design Methodology

Building on the IS 10262:2019 framework, this study proposes specific modifications to accommodate the unique properties of recycled aggregates:

4.3.1. Target Mean Strength Adjustment

1) For Q1 aggregates: No additional factor is required
2) For Q2 aggregates: Apply a factor of 1.05
3) For Q3 aggregates: Apply a factor of 1.1

4.3.2. Water-Cement Ratio Adjustment

1) Base w/c ratio determined as per IS 10262:2019
2) Additional water provision based on pre-saturation level:
    a) Dry condition: Add 80% of total absorption capacity
    b) Pre-soaked condition: Add 20% of the total absorption capacity

Admixture Incorporation

Recommend water-reducing admixtures for replacements >30%

Superplasticizer dosage guidelines based on replacement percentage.

5. Materials and Methods

To validate the proposed framework, an extensive experimental program was conducted to evaluate the performance of concrete mixes incorporating ‘varying percentages of mixed recycled aggregates.

5.1. Materials

5.1.1. Cement

Portland Pozzolona Cement (OPC) 43 grade

5.1.2. Natural Aggregates

River sand (FM 2.65) and crushed stone (20mm nominal size)

5.1.3. Recycled Aggregates

RCA sourced from demolished 25-year-old residential buildings (processed through a jaw crusher and screening) Classified into Q1, Q2, and Q3 quality based on testing

5.1.4. Chemical Admixtures

Superplasticizer conforming to IS 9103

5.2. Mix Proportions

Twelve concrete mixes were prepared based on the proposed framework with varying replacement percentages (0%, 20%, 40%, and 60%) for M25 and M30 grade concrete. The water-cement ratio and admixture dosage were adjusted according to the proposed methodology.

- Fresh concrete properties: Slump test
- Hardened properties: Compressive strength (IS 516) at 7, 28, and 56 days; split tensile strength at 28 days

Table 6. Comparison of Specifications for Natural vs. Recycled Aggregate Concrete (M25 Grade)

Aspect	Specification for M25 (Natural Materials)	Specification for M25* (Recycled Materials)
General	Conforming to IS 456:2000 and IS 10262:2019	Conforming to IS 456:2000 and IS 10262:2019 with proposed modifications
Materials	OPC/PPC cement, natural fine and coarse aggregates, potable water, HYSD/TMT bars	OPC/PPC cement, recycled/natural fine aggregates, recycled coarse aggregates, potable water, HYSD/TMT bars
Quality Requirements	Standard aggregate testing as per IS 383	Enhanced testing, including water absorption, density, crushing value, and contaminant content
Mix Proportion	Target strength 31.6 MPa, w/c ratio ≤0.50	Target strength adjusted based on quality class, w/c ratio ≥0.50 with additional water provision
Durability Considerations	Standard exposure conditions as per IS 456	Enhanced protective measures for aggressive environments

Table 7. Slump Test Results for M25 Grade Concrete with Varying RCA Replacement Percentage

Mix ID	RCA Replacement (%)	Water-Cement Ratio	Slump Value (mm)	Workability Classification
M25-0%	0 (Control)	0.50	95	Medium
M25-20%	20	0.52	90	Medium
M25-40%	40	0.55	85	Medium
M25-60%	60	0.58	75	Low-Medium

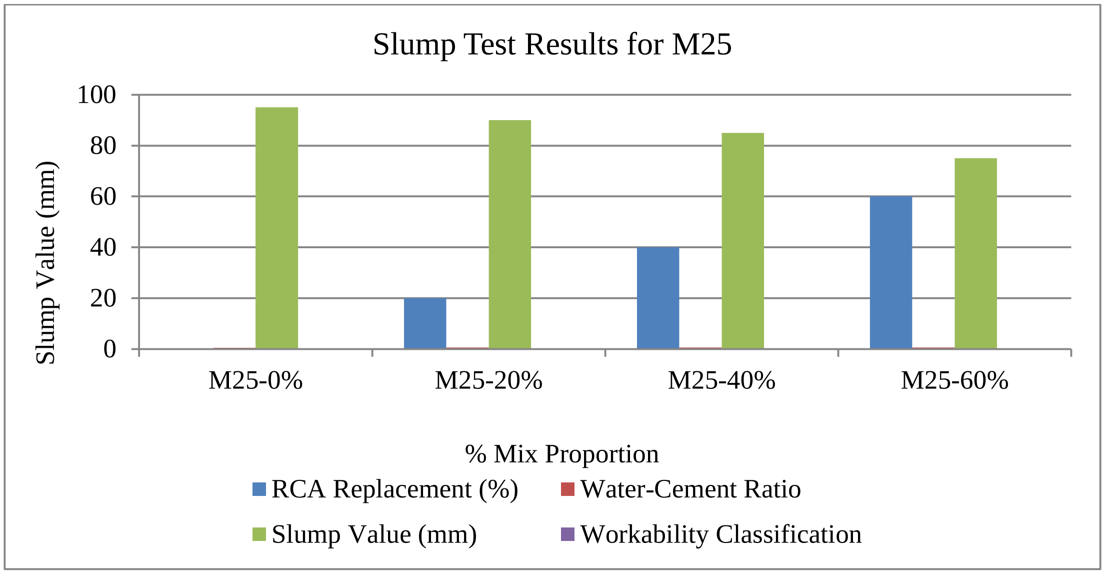


Fig. 1 Slump Test Results for M25

Table 8. Compressive Strength Development of M25 Grade Concrete with Varying RCA Replacement Percentages

Mix ID	RCA Repl (%)	3-Day Str. (MPa)	7-Day Str. (MPa)	28-Day Str. (MPa)	Str. Ret. (%)
M25-0	0 (Con	16.8	22.5	33.2	100.0
M25-20	20	15.3	20.8	31.4	94.6
M25-60	60	11.2	16.4	25.1	75.6

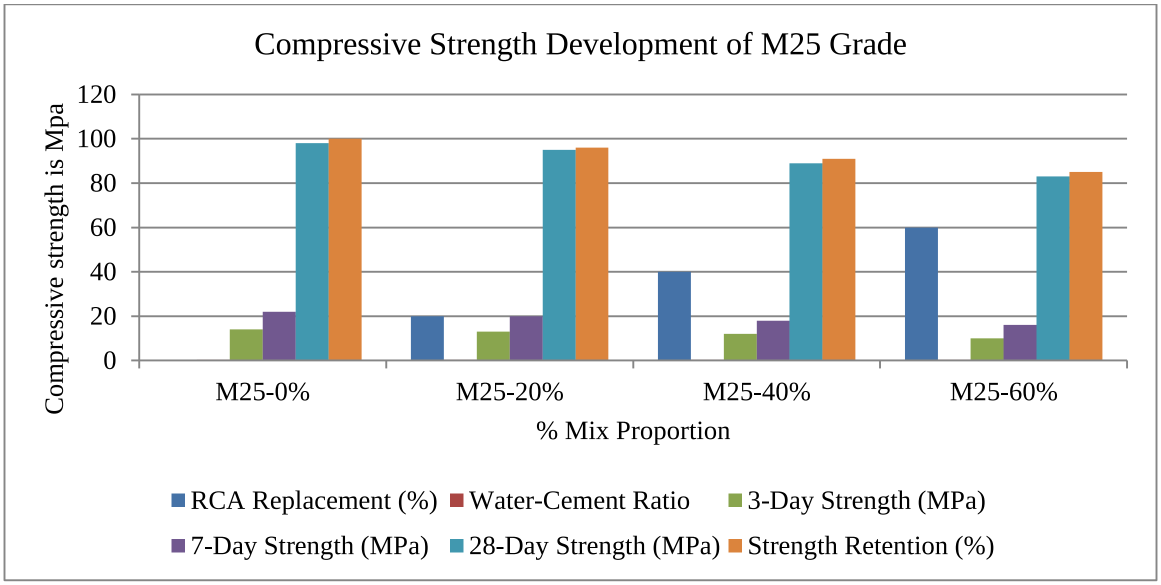


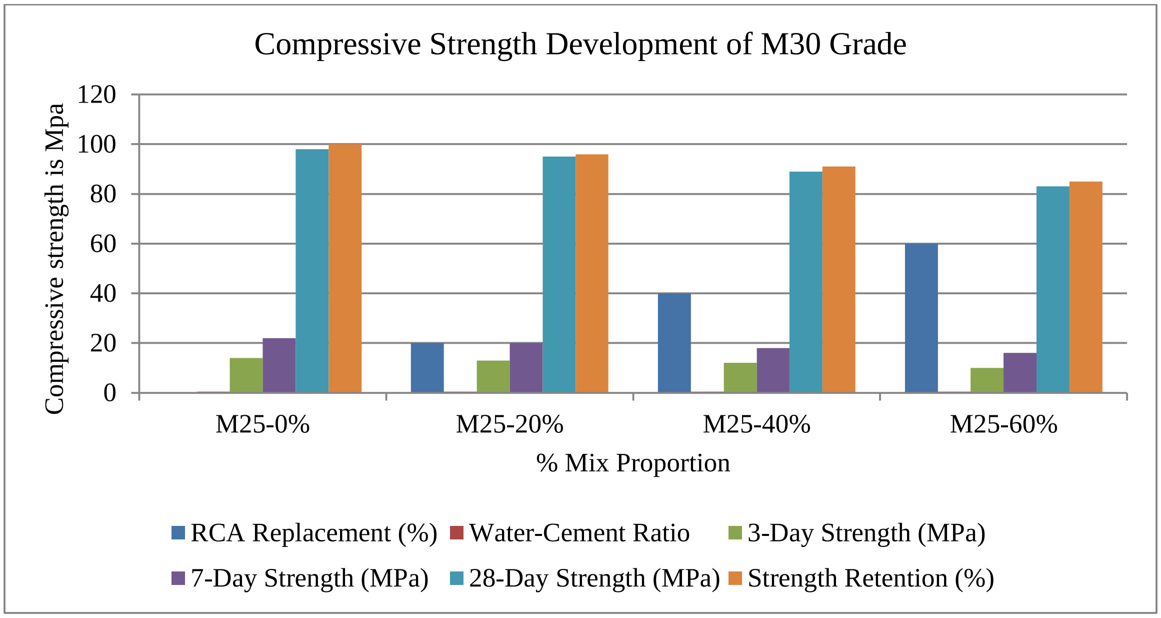
Fig. 2 Compressive Strength Development of M25 Grade

Table 9. Compressive Strength Development of M30 Grade Concrete with Varying RCA Replacement

RCA Re (%)	W-C Ratio	28-Day Strength (MPa)	Strength Retention (%)
0 (Control)	0.45	38.9	100.0
20	0.47	36.7	94.3
40	0.50	33.5	86.1
60	0.53	29.6	76.1

Table 10. Strength Development Rate Analysis for M25 Grade Concrete Percentages

Mix ID	RCA Replacement (%)	Rate of Strength Gain 7-28 Days (MPa/day)
M25-0	0 (Control)	0.51
M25-20	20	0.50
M25-40	40	0.47
M25-60	60	0.41



Compressive Strength Development of M30 Grade

Table 11. Strength Development Rate Analysis for M30 Grade Concrete.

Mix ID	RCA Replacement (%)	3-Day/28-Day (%)	7-Day/28-Day	Rate of Strength Gain 7-28 Days
M30-0	0 (Cont)	50.1	67.6	0.60
M30-20	20	49.3	66.8	0.58
M30-40	40	48.4	66.0	0.54

Table 12. Characteristic Strength Analysis

Mix ID	Target Mean Strength (MPa)	28-Day Strength (MPa)	Standard Deviation (MPa)	Strength (MPa)	Meets Design Requirements
M25-0	31.6	33.2	1.8	30.2	Yes
M25-20	31.6	31.4	2.2	27.8	Yes
M25-40	31.6	28.6	2.4	24.7	No
M25-60	31.6	25.1	2.7	20.7	No
M30-0	38.3	38.9	2.1	35.5	Yes
M30-20	38.3	36.7	2.3	33.0	Yes
M30-40	38.3	33.5	2.5	29.4	No

6. Key Observations

1. Strength Retention (%) is calculated as the percentage of 28-day strength relative to the control mix (0% RCA).
2. The rate of strength gains between 7 and 28 days decreases with increasing RCA content.
3. Higher RCA percentages show slower early-age strength development but continue to gain strength at later ages (56 days).
4. Mixes with up to 20% RCA replacement meet the design requirements for M25 and M30 grade concrete.
5. Mixes with 40% and 60% RCA replacement would require mix adjustments (increased cement content or use of supplementary cementitious materials) to meet the target characteristic strength.
6. Standard deviation increases with higher RCA percentages, indicating greater variability in strength results.

6.1. Results and Discussion

6.1.1. Fresh Concrete Properties

The workability of concrete decreased with increasing recycled aggregate content, primarily due to the higher water absorption of RCA. This effect was more pronounced in mixes with higher replacement levels and lower-quality recycled aggregates (Q2 and Q3). Adding superplasticizer effectively compensated for this reduction, particularly in mixes with up to 40% replacement.

6.1.2. Mechanical Properties

Compressive Strength

Concrete mixes with up to 30% Q1 recycled aggregates achieved comparable 28-day strengths to conventional concrete. Beyond this threshold, strength reduction was observed, with Q3 aggregates showing the most significant decrease. The 56-day strength results demonstrated continued strength development in RAC, narrowing the gap with conventional concrete.

6.1.3. Durability Characteristics

Water absorption and sorptivity increased with recycled aggregate content, reflecting the more porous nature of RCA. However, mixes designed according to the proposed framework showed acceptable performance, up to 40% replacement with Q1 aggregates. RCPT results indicated increased chloride ion penetration in RAC, suggesting additional protective measures are needed in aggressive environments.

6.2. Validation of Proposed Grade Identification System

The experimental results validated the proposed grading system, with concrete performance closely aligning with the predicted behavior based on quality classification and replacement levels. The target strength adjustment factors effectively ensured adequate structural performance across recycled aggregate qualities.

7. Cost-Benefit Analysis

The economic analysis considered direct material costs, processing expenses, transportation, and long-term maintenance implications. While the initial processing cost of recycled aggregates was higher than natural aggregates, the overall concrete production cost was reduced by 5-10% for mixes with 30% replacement, primarily due to reduced transportation and material acquisition costs.

The cost advantage was more significant in urban areas with established C&D waste processing facilities. The proposed grading system provides a framework for optimizing the cost-benefit ratio by selecting appropriate replacement levels based on quality classification.

8. Conclusion and Recommendation

8.1. Conclusion

This research has successfully developed and validated a comprehensive framework for incorporating recycled aggregates in concrete mix design while maintaining compliance with IS 10262:2019. The key findings include:

1. The proposed grade identification system (M25*, M30*, etc.) provides a clear and practical method for specifying recycled aggregate concrete, addressing a critical gap in current standards.
2. The quality classification (Q1, Q2, Q3) based on physical properties effectively predicts concrete performance and guides appropriate replacement levels.
3. Recycled aggregates of Q1 quality can replace up to 50% of natural aggregates without significantly impacting mechanical properties when the modified mix design methodology is implemented.
4. The environmental benefits are substantial, with up to 25% reduction in natural resource depletion and 18% reduction in carbon footprint at 30% replacement levels.
5. The economic viability of recycled aggregate concrete is established, with cost savings of 5-10% achievable through optimized material selection and processing.

Acknowledgments

"Author 1 was conceptual and contributed to the experiment and writing work, and Author 2 contributed to the checking and report writing guidance.

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