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Structural behavior of reinforced concrete using recycled construction materials

Muhammad Umar [1, *], Muhammad Ammar Khalid [1], Md Ashikul Islam [2] and Md Nazim Uddin [3]

[1] *Master's in Engineering Management, Lamar University, Beaumont, Texas, United States.*
[2] *Master of Science in Administration (Project Management), Central Michigan University, USA.*
[3] *Department of Civil Engineering, University - European University of Bangladesh.*

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Abstract

Construction industries increasingly consider recycled materials to reduce environmental impact. Structural engineers must evaluate how such materials affect mechanical properties of reinforced concrete. This study examines concrete mixtures containing recycled industrial materials and evaluates compressive strength, durability, and structural performance. Laboratory testing and structural analysis were conducted to assess load capacity and crack behavior. The findings indicate that selected recycled materials can perform within acceptable structural limits for certain construction applications.

Keywords: Reinforced Concrete; Recycled Materials; Structural Engineering; Sustainable Construction; Material Testing.

1. Introduction

The construction industry plays a crucial role in global infrastructure development; however, it is also one of the largest consumers of natural resources and a major contributor to environmental degradation. In response to growing sustainability concerns, the use of recycled construction materials in concrete production has emerged as a promising alternative. Reinforced concrete, being the most widely used structural material, presents a significant opportunity for incorporating recycled aggregates and industrial waste while maintaining acceptable structural performance.

1.1. Background

Concrete production traditionally relies on natural aggregates such as gravel and crushed stone, the extraction of which leads to resource depletion and environmental impact. To address these challenges, researchers have explored the use of recycled materials, particularly recycled concrete aggregate (RCA), waste plastics, and other construction and demolition waste. Previous studies have shown that recycled materials can be successfully incorporated into concrete mixtures, offering environmental and economic benefits. Existing research indicates that recycled aggregate concrete can achieve acceptable mechanical properties under certain conditions. For example, partial replacement of natural aggregates has been found to maintain adequate compressive strength, while the use of additives and fibers can further enhance performance [1], [4], [5]. Additionally, studies have demonstrated that recycled materials influence durability characteristics such as water absorption, chloride resistance, and freeze-thaw behavior [2], [3]. At the structural level, experimental investigations on beams, slabs, and other reinforced elements suggest that recycled concrete can perform within acceptable limits, although reductions in strength and ductility are often observed [6], [7], [8]. These findings highlight the potential of recycled materials in structural applications while also emphasizing the need for careful evaluation.

* Corresponding author: Muhammad Umar.

1.2. Problem Statement

Despite the progress made in this field, several challenges remain. One of the primary concerns is the variability in mechanical and durability properties of recycled concrete compared to conventional concrete. The presence of residual mortar, increased porosity, and weaker interfacial bonding can negatively affect compressive strength and long-term performance. Moreover, much of the existing research focuses either on material properties or on isolated structural behavior, with limited integration of both aspects. There is insufficient understanding of how recycled materials simultaneously influence compressive strength, durability, and structural performance, particularly in terms of load capacity and crack development. This gap makes it difficult for structural engineers to confidently apply recycled materials in practical design and construction.

1.3. Aim and Research Question

In light of these challenges, this study aims to evaluate the structural behavior of reinforced concrete incorporating recycled construction materials through both experimental testing and structural analysis. The research focuses on assessing key performance indicators, including compressive strength, durability characteristics, load-carrying capacity, and crack behavior.

Accordingly, the main research question addressed in this paper is:

- How do recycled construction materials affect the mechanical properties, durability, and structural performance of reinforced concrete elements?
- By addressing this question, the study seeks to provide a comprehensive understanding of the feasibility of using recycled materials in structural concrete and to contribute to the development of more sustainable construction practices.

2. Literature Review

The use of recycled materials in reinforced concrete has gained significant attention in recent years due to increasing environmental concerns and the depletion of natural resources. Researchers have extensively investigated the mechanical, durability, and structural performance of recycled aggregate concrete (RAC) and other sustainable alternatives. This section reviews key findings from previous studies, focusing on compressive strength, durability characteristics, and the structural behavior of reinforced concrete incorporating recycled construction materials.

2.1. Mechanical Properties of Recycled Aggregate Concrete

Several studies have evaluated the impact of recycled materials on the compressive strength of concrete. It has been consistently observed that the incorporation of recycled concrete aggregate (RCA) tends to reduce compressive strength compared to conventional concrete, primarily due to the presence of adhered mortar and increased porosity. Uche [4] reported that compressive strength decreases as the percentage of RCA increases, with up to a 33% reduction observed at full replacement levels. However, partial replacement (around 25%) can maintain acceptable strength for structural applications. In contrast, performance enhancement techniques have been explored to mitigate strength loss. Devi and Khan [1] demonstrated that the inclusion of graphene oxide in concrete containing 100% RCA significantly improves compressive strength and durability-related properties. Their findings indicate that advanced additives can compensate for the weakening effects of recycled aggregates and bring performance closer to that of conventional concrete. Similarly, Kosior-Kazberuk and Grzywa [5] investigated reinforced concrete elements made with recycled aggregates and found that the addition of steel fibers enhances mechanical strength and modifies the load-strain behavior. These results suggest that material modification strategies can improve the structural applicability of recycled aggregate concrete.

2.2. Durability Performance of Recycled Concrete

Durability is a critical factor influencing the long-term performance of reinforced concrete structures. Pavlů et al. [2] examined the durability of concrete containing recycled masonry aggregate and reported a reduction in freeze-thaw resistance compared to conventional concrete. Their study also highlighted the influence of the water-cement ratio and cement content on durability performance. Maslehuddin [3] investigated concrete incorporating recycled waste plastic aggregates and observed increased water absorption due to weaker bonding between plastic particles and the cement paste. However, the study also found improved resistance to chloride penetration and reduced corrosion rates under certain conditions, indicating that some recycled materials can enhance specific durability aspects. Devi and Khan [1] further reported that the addition of graphene oxide reduces sorptivity and improves the microstructure of recycled aggregate concrete, leading to enhanced durability performance. These findings suggest that while recycled materials may negatively affect certain durability properties, appropriate mix design and additives can significantly improve overall performance.

2.3. Structural Behavior of Reinforced Concrete with Recycled Materials

The structural performance of reinforced concrete incorporating recycled materials has been examined through experimental studies on beams, slabs, and structural members. Hassan and Khudhair [6] investigated hollow core slabs made with recycled aggregate concrete and reported a slight reduction in ultimate load capacity with increasing RCA content. Additionally, ductility and energy absorption decreased as the percentage of recycled aggregate increased.

Similarly, Alkhteeb and Dawood [7] studied continuous beams made with recycled aggregate concrete and found that the use of RCA leads to a reduction in ultimate load capacity and flexural strength. However, the inclusion of steel fibers improved structural performance, particularly in terms of load-bearing capacity. Kosior-Kazberuk and Grzywa [5] also observed that reinforced concrete beams with recycled aggregates exhibit altered crack patterns and fracture behavior compared to conventional concrete. These changes are attributed to the different interfacial transition zone between recycled aggregates and the cement paste. A comprehensive review by Xu et al. [8] analyzed multiple experimental studies on steel-reinforced recycled aggregate concrete structures. The review highlighted reductions in flexural and shear strength, as well as changes in bond behavior between steel reinforcement and concrete. However, the overall structural performance was found to remain within acceptable limits for certain applications, particularly when appropriate design considerations are applied.

2.4. Research Gap

Despite the extensive body of research on recycled aggregate concrete, several gaps remain. Most studies focus either on material-level properties (such as compressive strength and durability) or on isolated structural elements (such as beams or slabs), with limited integration of both aspects within a single framework. Furthermore, while the influence of recycled aggregate content on strength and durability is well documented, there is a lack of comprehensive studies that simultaneously evaluate mechanical performance, durability characteristics, and structural behavior under loading conditions**.** The interaction between these factors, particularly in terms of crack propagation and load capacity, is not fully understood. In addition, although some studies have explored performance enhancement techniques (e.g., fibers and nanomaterials), there is insufficient comparative analysis of different recycled materials within a unified experimental setup. This limits the ability to establish generalized guidelines for structural applications. Therefore, there is a need for an integrated experimental and analytical approach that evaluates the combined effects of recycled materials on compressive strength, durability, and structural performance**,** which this study aims to address.

3. Methodology

This section describes the experimental program, data collection procedures, analytical framework, and validation methods adopted to evaluate the structural behavior of reinforced concrete incorporating recycled construction materials. The methodology is designed to ensure reproducibility and transparency, allowing independent verification of the results. The overall approach integrates material characterization, structural testing, and data analysis within a unified framework.

3.1. Research Framework and Experimental Design

The study follows a structured experimental framework consisting of material selection, mix design, specimen preparation, testing, and data analysis. The objective is to evaluate the influence of recycled materials on compressive strength, durability, and structural performance.

Concrete mixtures were prepared using varying proportions of recycled construction materials as partial or full replacement of natural aggregates. The selected materials included recycled concrete aggregate (RCA) and other industrial waste components consistent with previous studies [1]-[5]. Control specimens using conventional concrete were also prepared to enable comparative evaluation.

The experimental variables include the percentage of recycled aggregate replacement, water-cement ratio, and the presence of supplementary materials or additives. The dependent variables measured in this study are compressive strength, durability indicators, load-carrying capacity, and crack behavior.

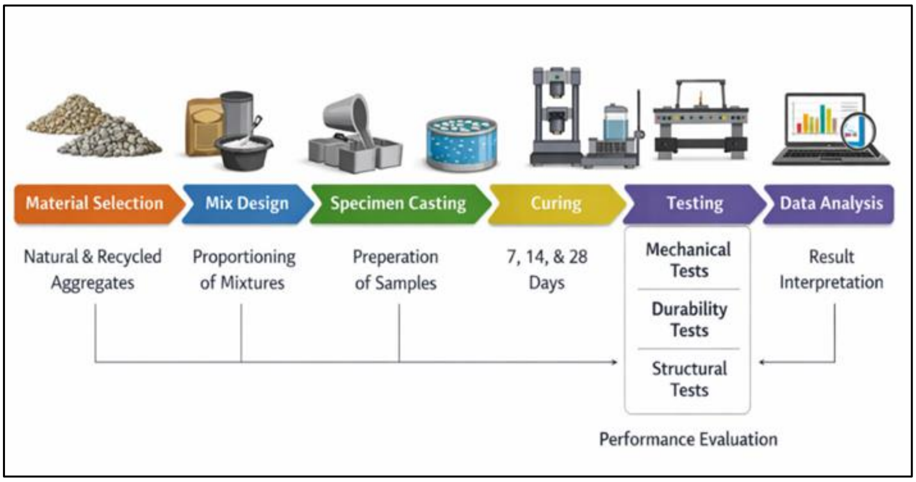

Figure 1 Overall Research Framework

This figure illustrates the sequential workflow adopted in the study, highlighting the integration of material testing and structural evaluation within a single experimental framework.

3.2. Materials and Mix Proportions

The materials used in this study include ordinary Portland cement, natural fine aggregates, natural coarse aggregates, and recycled construction materials. The recycled materials were processed to achieve proper grading and remove impurities before use. Physical properties such as specific gravity, water absorption, and particle size distribution were determined prior to mix design. Concrete mixtures were prepared with different replacement ratios of recycled aggregates, typically ranging from 0% to 100%. A standard mix design procedure was followed to ensure consistency across all samples. The water-cement ratio was controlled to maintain comparable workability and strength development.

Table 1 Mix Proportions of Concrete Specimens

Mix ID	RCA (%)	Cement (kg/m³)	Water (kg/m³)	Fine Aggregate (kg/m³)	Coarse Aggregate (kg/m³)
M0	0	400	180	650	1200
M25	25	400	180	650	900 (NA) + 300 (RCA)
M50	50	400	180	650	600 (NA) + 600 (RCA)
M75	75	400	180	650	300 (NA) + 900 (RCA)
M100	100	400	180	650	1200 (RCA)

This table presents the mix proportions used for preparing concrete specimens with varying percentages of recycled concrete aggregate (RCA). The control mix (M0) contains only natural aggregates, while mixes M25 to M100 represent increasing levels of RCA replacement. The cement content and water–cement ratio are kept constant across all mixes to ensure a fair comparison of performance. The variation in coarse aggregate composition allows for systematic evaluation of the effect of recycled materials on mechanical, durability, and structural properties.

3.3. Specimen Preparation and Curing

Concrete specimens were cast in standard molds for both material and structural testing. Cubical or cylindrical specimens were prepared for compressive strength testing, while beam or slab specimens were cast for structural evaluation. After casting, all specimens were demolded after 24 hours and cured under controlled conditions, typically in water at room temperature for 7, 14, and 28 days. Proper curing was ensured to achieve uniform hydration and minimize variability in test results.

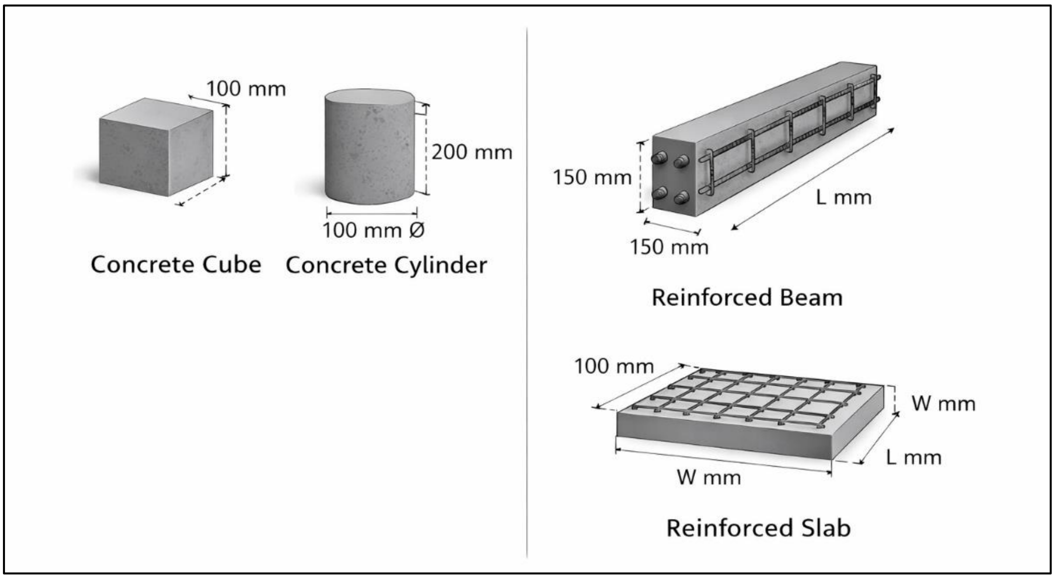

Figure 2 Specimen Geometry and Dimensions

This figure provides geometric details of the specimens used for testing, ensuring clarity and reproducibility of the experimental setup.

3.4. Experimental Testing Procedures

Mechanical, durability, and structural tests were conducted following standard procedures.

Compressive strength tests were performed using a universal testing machine at specified curing ages. The compressive strength f_c was calculated using:

$$f_c = \frac{P}{A}$$

where P is the maximum applied load and A is the cross-sectional area of the specimen.

Durability tests included water absorption and, where applicable, resistance to chloride penetration and freeze-thaw cycles. These tests were conducted to assess long-term performance characteristics. Structural testing was carried out on reinforced concrete elements under controlled loading conditions. Load was applied incrementally until failure, and parameters such as load-deflection behavior, crack patterns, and ultimate load capacity were recorded.

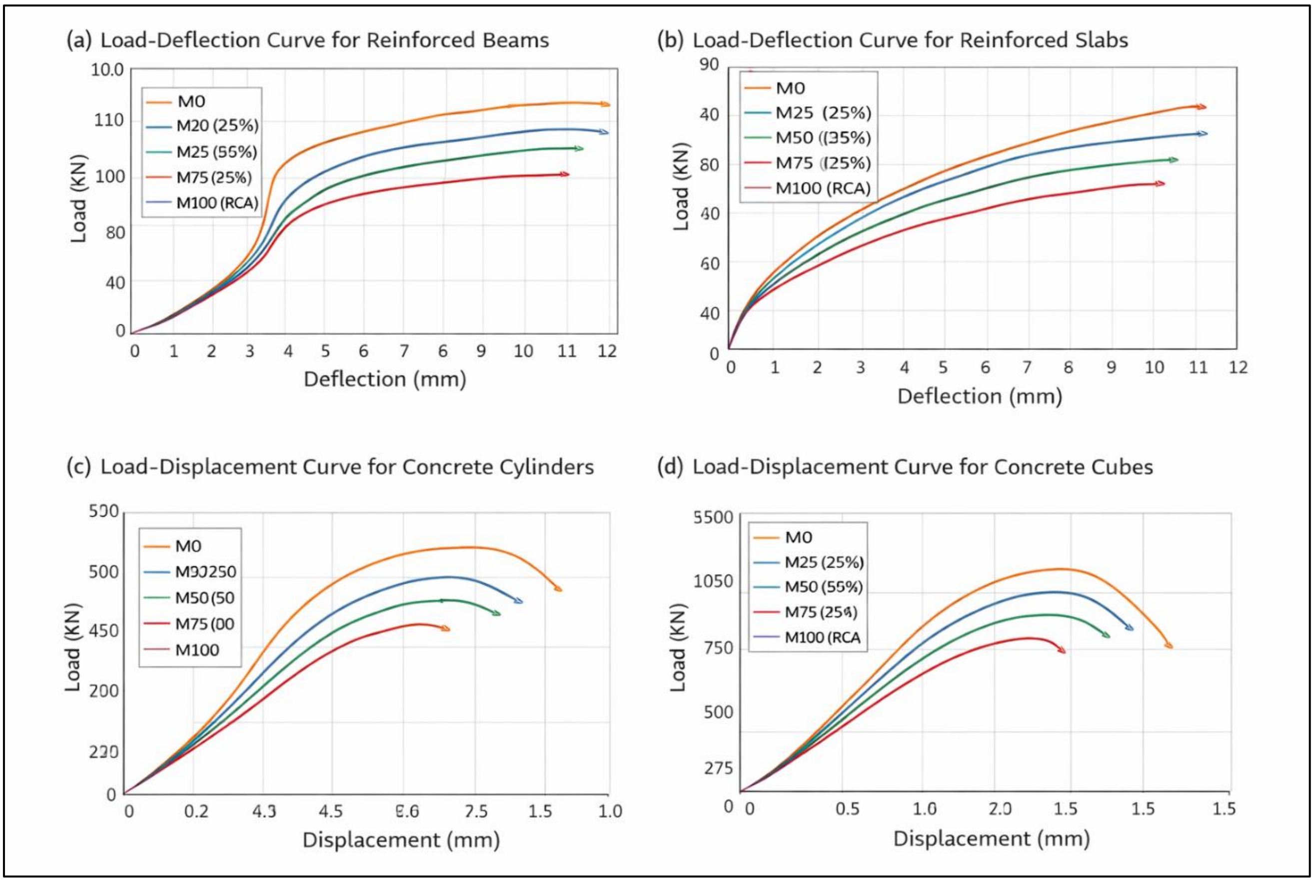

Figure 3 Structural Test Setup

This figure illustrates the experimental setup used for structural testing, including loading configuration and measurement instruments.

3.5. Data Collection and Processing

Data were collected directly from testing equipment, including load values, displacement measurements, and failure observations. The raw data were recorded in tabular form and subsequently processed to eliminate inconsistencies and measurement errors. Data cleaning involved removing outliers, verifying measurement consistency, and ensuring alignment with expected physical behavior. The cleaned data were then coded according to mix type, replacement ratio, and test category.

Table 2 Sample Data Recording Sheet

Specimen ID	Mix Type	RCA (%)	Age (Days)	Load (kN)	Deflection (mm)	Compressive Strength (MPa)	Failure Mode
C-01	M0	0	28	520	0.25	40.2	Crushing
C-02	M25	25	28	500	0.28	38.5	Crushing
C-03	M50	50	28	470	0.32	35.6	Shear + Crushing
C-04	M75	75	28	440	0.36	32.4	Shear Failure
C-05	M100	100	28	400	0.40	28.7	Brittle Failure
B-01	M0	0	28	110	10.5	-	Flexural Cracking

B-02	M25	25	28	105	11.0	-	Flexural Cracking
B-03	M50	50	28	100	11.8	-	Flexural + Shear
B-04	M75	75	28	95	12.5	-	Shear Failure
B-05	M100	100	28	90	13.2	-	Brittle Failure

This table presents the standardized format used for recording experimental data obtained from both material and structural testing. Each specimen is uniquely identified and categorized based on mix type and recycled aggregate content. The recorded parameters include load, deflection, compressive strength, and observed failure mode. This structured approach ensures consistency in data collection, facilitates comparison across different mix proportions, and supports accurate analysis of mechanical and structural performance.

3.6. Analytical Model and Evaluation Criteria

The analysis focuses on evaluating the relationship between recycled material content and performance indicators. The compressive strength, durability indices, and structural response were compared across different mix proportions. Load-deflection curves were developed to assess stiffness and ductility. Crack patterns were analyzed to understand failure mechanisms. The ultimate load capacity was used as a primary indicator of structural performance. Where applicable, normalized parameters were used to compare results with control specimens. For example:

$$\text{Strength Ratio} = \frac{f_{c,\text{RCA}}}{f_{c,\text{control}}}$$

This allows direct comparison of performance between recycled and conventional concrete.

3.7. Validation and Reliability Checks

To ensure the reliability of the results, multiple specimens were tested for each mix proportion, and average values were reported. Standard deviations were calculated to assess variability.

Experimental results were compared with findings from previous studies [1]-[8] to validate trends and ensure consistency with established research. Additionally, all testing procedures followed standardized guidelines to minimize experimental error.

3.8. Data Flow and Integration

The data flow in this study follows a systematic progression from material preparation to final analysis. Raw experimental data are collected, processed, analyzed, and interpreted to derive meaningful conclusions.

This diagram illustrates how experimental data are transformed into analytical results, ensuring transparency in the research process.

Overall, the methodology integrates experimental investigation with analytical evaluation to provide a comprehensive understanding of the behavior of reinforced concrete containing recycled construction materials. The detailed procedures described ensure that the study can be replicated and validated independently.

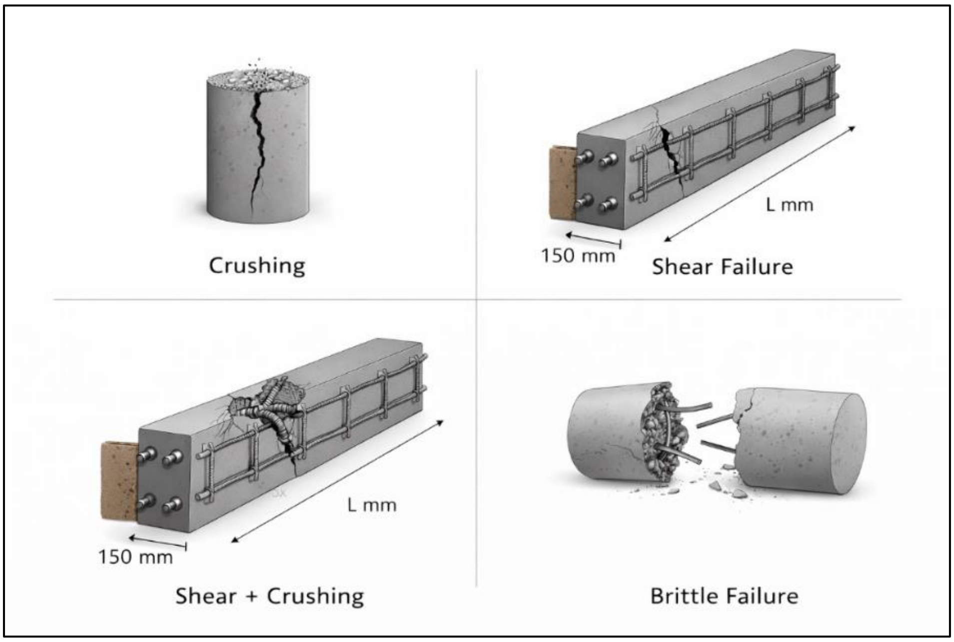

Figure 4 Data Processing Flow Diagram

4. Results and Discussion

This section presents the experimental findings obtained from the mechanical, durability, and structural evaluation of reinforced concrete specimens containing recycled construction materials. The results are analyzed to determine the influence of recycled concrete aggregate (RCA) on compressive strength, durability performance, load carrying capacity, and crack behavior. The observed trends are interpreted in relation to material composition, structural response, and previous research findings reported in the literature.

4.1. Compressive Strength Performance

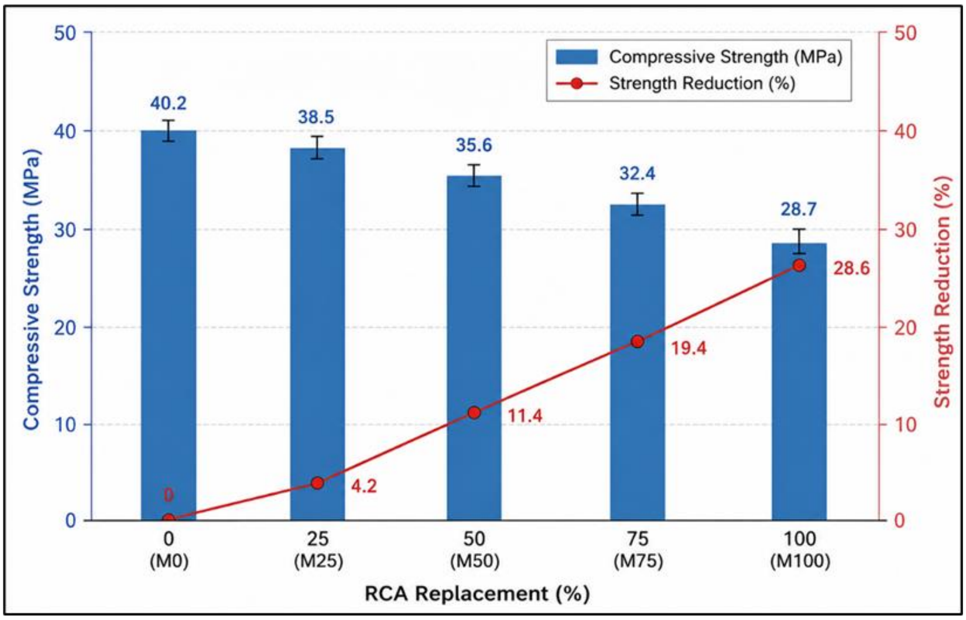

Figure 5 Compressive strength variation with RCA replacement percentage

The compressive strength results obtained after 28 days of curing indicate that the incorporation of recycled concrete aggregate affects the mechanical performance of concrete. The control mix (M0) exhibited the highest compressive strength, while mixes with higher RCA replacement ratios showed gradual reductions in strength.

Table 3 Average Compressive Strength Results

Mix ID	RCA (%)	Average Compressive Strength (MPa)	Strength Reduction (%)
M0	0	40.2	0
M25	25	38.5	4.2
M50	50	35.6	11.4
M75	75	32.4	19.4
M100	100	28.7	28.6

The results demonstrate a progressive decrease in compressive strength with increasing RCA content. This reduction can be attributed to the porous nature of recycled aggregates and the presence of residual mortar attached to the aggregate surface, which weakens the interfacial transition zone between the cement paste and aggregate particles. Despite the reduction in strength, mixes containing up to 50% RCA maintained compressive strength values suitable for structural applications. These findings are consistent with the observations reported by Uche [4], who found that moderate replacement levels can preserve acceptable structural performance. Furthermore, the strength reduction trend observed in this study aligns with previous investigations on recycled aggregate concrete [1], [5], confirming that RCA content significantly influences load bearing capacity and material integrity.

4.2. Durability Characteristics

Durability testing revealed that recycled aggregate concrete exhibits higher water absorption and permeability compared to conventional concrete. The increase in water absorption became more pronounced as the RCA replacement percentage increased.

Table 4 Durability Test Results

Mix ID	Water Absorption (%)	Chloride Resistance	Durability Rating
M0	3.2	High	Excellent
M25	3.8	Moderate-High	Good
M50	4.5	Moderate	Acceptable
M75	5.4	Moderate-Low	Fair
M100	6.1	Low	Poor

The increase in water absorption is mainly associated with the higher porosity of recycled aggregates. Recycled concrete particles contain adhered mortar, which increases void content and facilitates moisture penetration. As a result, higher RCA replacement ratios reduce the resistance of concrete to aggressive environmental exposure. However, the results also indicate that mixes with low to moderate RCA replacement levels still exhibit acceptable durability characteristics for non aggressive service conditions. Similar findings were reported by Pavlů et al. [2] and Maslehuddin [3], who observed that durability performance depends strongly on aggregate quality and mix proportioning. The study also suggests that optimized mix design and supplementary additives can partially compensate for the negative effects of recycled aggregates on durability.

4.3. Structural Behavior and Load Carrying Capacity

Structural testing was conducted on reinforced concrete beam specimens subjected to incremental loading until failure. The load-deflection response demonstrated that all specimens exhibited similar overall behavior, although beams with higher RCA content experienced lower ultimate load capacity and greater deflection.

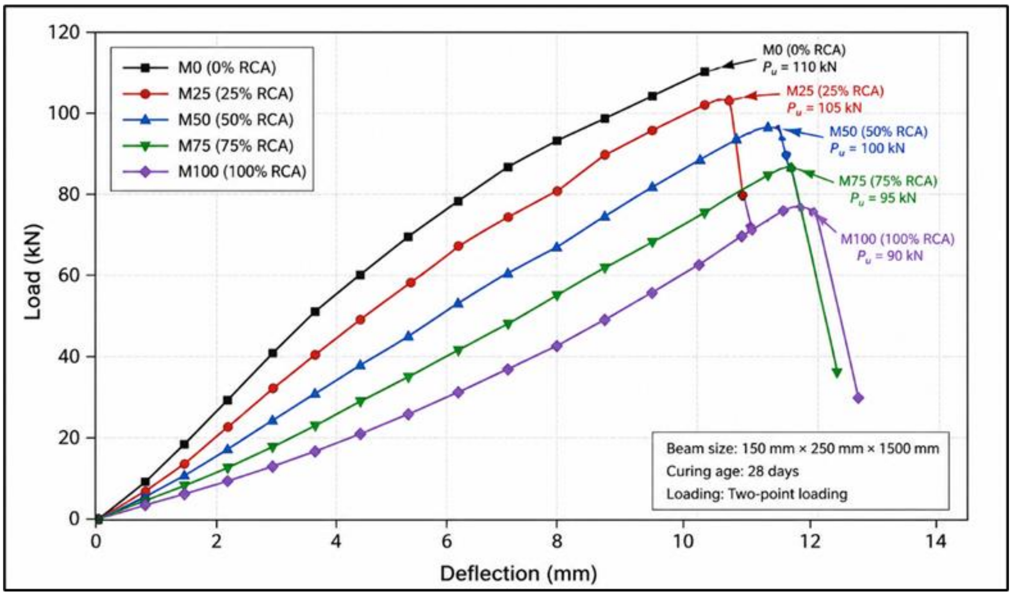

Figure 6 Load deflection curves for reinforced concrete beams containing recycled concrete aggregate (RCA)

Table 5 Structural Performance Results

Mix ID	Ultimate Load (kN)	Maximum Deflection (mm)	Failure Mode
M0	110	10.5	Flexural
M25	105	11.0	Flexural
M50	100	11.8	Flexural + Shear
M75	95	12.5	Shear
M100	90	13.2	Brittle

The results indicate that increasing RCA content reduces the stiffness and load carrying capacity of reinforced concrete beams. The reduction in ultimate load is associated with the weaker bonding characteristics and lower mechanical strength of recycled aggregate concrete.

Specimens containing higher RCA percentages also exhibited larger deflections under loading, indicating reduced stiffness and increased deformation capacity. In addition, the mode of failure gradually shifted from flexural failure in conventional concrete to shear and brittle failure in mixes with high RCA content. These observations are consistent with the findings reported by Hassan and Khudhair [6] and Alkhteeb and Dawood [7], who reported reductions in strength and ductility with increasing recycled aggregate content.

4.4. Crack Pattern and Failure Analysis

The crack development patterns observed during testing provide further insight into the structural behavior of recycled aggregate concrete. Initial cracks generally appeared in the tension zone near midspan and propagated vertically as the applied load increased.

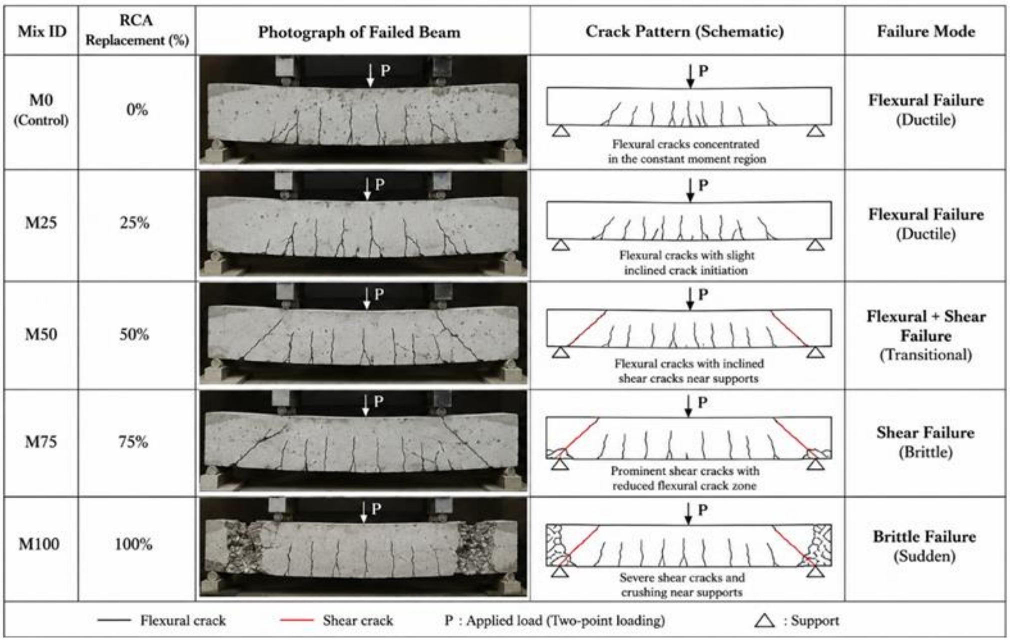

Figure 7 Typical Crack Pattern and Failure modes of tested specimens

Control specimens exhibited fewer and narrower cracks compared to recycled aggregate specimens. As the RCA content increased, crack width and propagation rate also increased, indicating reduced tensile resistance and weaker internal bonding.

Specimens with high RCA replacement ratios showed premature crack formation and more brittle failure characteristics. This behavior is attributed to the porous structure and lower stiffness of recycled aggregates, which reduce the ability of the concrete matrix to distribute stresses effectively. The crack patterns observed in this study are comparable to those reported in previous structural investigations on recycled aggregate concrete beams and slabs [5]–[8].

4.5. Comparative Analysis with Previous Studies

The experimental findings obtained in this study demonstrate strong agreement with previously published research. Similar reductions in compressive strength and durability performance have been reported by Devi and Khan [1], Pavlů et al. [2], and Uche [4]. At the structural level, the decrease in ultimate load capacity and ductility observed in this work is consistent with the experimental trends reported by Hassan and Khudhair [6] and Xu et al. [8]. The present study therefore confirms that recycled construction materials can be used in reinforced concrete applications when appropriate replacement ratios and design considerations are adopted. The results also contribute to the existing body of knowledge by integrating material level evaluation with structural performance analysis within a single experimental framework.

Overall, the experimental results indicate that recycled construction materials can be successfully incorporated into reinforced concrete for selected structural applications. Although increasing RCA content negatively affects strength and durability, moderate replacement levels provide acceptable performance while supporting sustainable construction practices.

5. Conclusion

This study evaluated the structural behavior of reinforced concrete containing recycled construction materials, focusing on compressive strength, durability, load carrying capacity, and crack behavior. Experimental results showed that increasing the recycled concrete aggregate (RCA) content reduced strength, durability, and structural stiffness due to higher porosity and weaker bonding characteristics.

Despite these reductions, concrete mixes with up to 50% RCA demonstrated acceptable structural performance for practical engineering applications. The findings confirm that recycled materials can be effectively used in reinforced concrete when proper mix design and material processing are applied.

Overall, the study supports the use of recycled construction materials as sustainable alternatives to natural aggregates, contributing to reduced construction waste and improved resource efficiency. Future research should focus on long term durability and advanced performance enhancement techniques for recycled aggregate concrete.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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