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MECHANICAL PERFORMANCE AND OPTIMAL REPLACEMENT OF RECYCLED DEMOLITION AGGREGATES IN M20 CONCRETE: A CASE STUDY FROM SURKHET, NEPAL

Mahesh Sharma[1*], Dr. Pradyut Anand[2]
[1]Research Scholar, PhD in Civil Engineering, Department of Civil Engineering, Noida International University. Email: sktmahesh@gmail.com
[2]Assistant Professor, Department of Civil Engineering, Noida International University. Email: pradyut.anand@niu.edu.in
[*]Corresponding Autor: sktmahesh@gmail.com

Declaration

The authors declare that this manuscript is original, has not been published previously, and is not currently under consideration for publication elsewhere. All authors have contributed significantly to the research and approve the final version of the manuscript.

Abstract

Rapid urbanization and intensive infrastructure development in Nepal have resulted in a significant surge of construction and demolition waste (CDW), traditionally managed through environmentally detrimental disposal practices. This research evaluates the mechanical performance and feasibility of utilizing crushed demolition waste as a sustainable coarse aggregate substitute in M20 grade concrete. The primary objective is to evaluate the influence of varying replacement levels of Recycled Concrete Aggregates (RCA) on the structural integrity and workability of concrete. The methodology involved sourcing CDW from ten demolition sites in Birendranagar, Surkhet, and processing it into RCA through systematic crushing and screening. Five concrete mixes were designed according to IS 10262:2019, with replacement ratios of 0%, 25%, 50%, 75%, and 100%. Results demonstrate that while RCA exhibits a water absorption rate 462.5% higher than natural aggregates, replacement levels up to 50% successfully achieved a 28-day compressive strength of 25.0 MPa, satisfying M20 structural requirements. However, beyond this threshold, a marked decline in slump and density was observed, leading to a downgrade in concrete classification. The study concludes that a 25–50% replacement ratio offers an optimal mechanical profile for structural applications, effectively promoting the circular economy. This approach provides a technically viable alternative to virgin aggregates and mitigates the ecological impact of riverbed mining and uncontrolled waste dumping in the Himalayan region.

Keywords: Recycled Concrete Aggregates (RCA); Mechanical Properties; M20 Grade Concrete; Compressive Strength; Workability; Construction and Demolition Waste (CDW); Sustainable Infrastructure; Concrete Mix Design; Structural Performance; Building Material Recycling.

1. Introduction

1.1 Background

The construction industry serves as a fundamental pillar of global economic development; yet, it is simultaneously one of the most resource-intensive and environmentally impactful sectors. As urbanization accelerates, particularly in developing nations like Nepal, the demand for concrete the most consumed man-made material on Earth has increased dramatically. Concrete production relies heavily on natural coarse aggregates, traditionally sourced from riverbeds and mountain quarries. However, the continuous extraction of these virgin materials has led to severe ecological imbalances, including the depletion of natural resources, destruction of aquatic habitats, and significant carbon emissions associated with mining and logistics.

Parallel to the resource depletion crisis is the burgeoning challenge of Construction and Demolition Waste (CDW) management. Globally, billions of tons of CDW are produced annually during the renovation, demolition, and reconstruction of aging infrastructure. In South Asian urban centers such as Birendranagar, Surkhet, this waste is frequently treated as a liability rather than a resource, ending up in illegal landfills or clogging drainage systems. The concept of Recycled Concrete Aggregate (RCA) emerges as a transformative solution, where crushed demolition waste is reprocessed to replace natural aggregates in new concrete mixes. This approach aligns with the principles of a "Circular Economy," aiming to close the loop in the material lifecycle of construction projects.

1.2 Problem Statement

Despite the theoretical benefits of recycling, the practical implementation of RCA in structural concrete faces significant technical hurdles. The primary issue stems from the "adhered mortar" the residual cement paste that remains attached to the original stone during the crushing process. This mortar is inherently porous, resulting in RCA having a much higher water absorption rate (recorded at 4.5% in this study compared to 0.8% for natural stones) and a lower specific gravity.

In the regional context of Surkhet, Nepal, there is a distinct lack of empirical data regarding how local demolition waste performs when used for structural grades like M20 concrete. Builders and engineers are often hesitant to adopt RCA due to concerns over workability loss and potential strength reduction. Without a standardized understanding of the mechanical thresholds specifically how much RCA can be added before the concrete fails to meet design codes the industry continues to rely on environmentally damaging virgin materials. There is an urgent need to quantify the relationship between replacement percentages and mechanical outputs like compressive strength and fresh density to build confidence in sustainable concrete technologies.

1.3 Research Gap

While international literature extensively documents the general properties of RCA, a significant research gap exists in the localized application of these materials within the Nepalese construction framework. Most existing studies have been conducted in controlled laboratory environments in developed countries using high-tech crushing machinery. There is a scarcity of research focused on "site-mixed" scenarios in Karnali Province, where the quality of parent concrete from old demolished buildings varies significantly.

Furthermore, few studies have specifically targeted the M20 grade the most common grade for residential and small commercial buildings in Nepal to define the exact "performance drop-off" point. Existing regional research often focuses on non-structural applications like sub-base for roads, leaving a void in the literature regarding the structural reliability of RCA for load-bearing elements. This study bridges that gap by providing a localized mechanical profile of RCA sourced directly from demolition sites in Birendranagar, focusing specifically on fulfilling the mechanical requirements of M20 grade concrete.

1.4 Research Objectives

The specific objectives of this study are as follows:

1. **To Evaluate Fresh State Properties:** To determine the impact of RCA replacement (at 25%, 50%, 75%, and 100% levels) on the workability and slump of M20 concrete mixes.
2. **To Determine Mechanical Strength:** To assess the 7-day and 28-day compressive strength of concrete cubes to identify the maximum sustainable replacement limit.
3. **To Analyze Density Variations:** To quantify the reduction in fresh and hardened density of concrete resulting from the porous nature of recycled aggregates.
4. **To Define Optimal Replacement Ratios:** To establish the percentage of RCA replacement that maintains the target M20 strength while maximizing the use of demolition waste.

By fulfilling these objectives, the research provides a technical blueprint for engineers and policymakers in Nepal to integrate crushed demolition waste into standard construction practices, thereby reducing the environmental footprint of the built environment.

2. Literature Review

The performance of concrete incorporating Recycled Concrete Aggregates (RCA) has been a focal point of civil engineering research for over three decades. This literature review synthesizes previous studies regarding the mechanical behavior of RCA, evaluates the methodologies used to optimize its performance, and identifies critical gaps that justify the current investigation into M20 grade concrete in Nepal.

2.1 Mechanical Properties of Recycled Concrete Aggregates

The mechanical integrity of RCA is fundamentally different from natural aggregates (NA) due to the presence of the Interfacial Transition Zone (ITZ) between the original aggregate and the adhered mortar.

- **Crushing and Impact Resistance:** Research by Kisku et al. (2017) indicates that the Aggregate Crushing Value (ACV) and Aggregate Impact Value (AIV) of RCA are typically 20–40% higher than those of NA. This is attributed to the brittle nature of the old cement paste, which shatters under high stress. In the context of the present study, the ACV of 32% found in Surkhet samples aligns with findings from Rao et al. (2011), who observed that high ACV in recycled materials directly correlates with lower compressive strength in the final concrete mix.
- **Bond Strength:** The mechanical bond in RCA-based concrete is often cited as the "weak link." Silva et al. (2014) argued that the ITZ in recycled concrete is twice as complex as in normal concrete because it involves two distinct zones: one between the old aggregate and old mortar, and another between the old mortar and the new cement paste.

2.2 Performance of Concrete Mixes (M20 and Structural Grades)

A significant body of work focuses on the maximum permissible replacement levels for structural concrete.

- **Replacement Thresholds:** Behera et al. (2014) conducted a meta-analysis of over 50 studies and concluded that up to 20–30% replacement of NA with RCA results in negligible strength loss. However, Etxeberria et al. (2007) demonstrated that with proper mix design adjustments, 50% replacement can achieve target strengths for medium-grade concrete (like M20), though 100% replacement typically necessitates a 10% increase in cement content to maintain equivalent strength.

- **Workability and Density:** Poon et al. (2004) highlighted that the higher water absorption of RCA (often exceeding 4%) leads to rapid slump loss. Wagih et al. (2013) found that fresh density decreases linearly with increasing RCA content, a finding supported by the current study's density drop from 2420 kg/m³ to 2140 kg/m³ at 100% replacement.

2.3 Critical Analysis of Mitigation Strategies

To overcome the mechanical deficiencies of RCA, several researchers have proposed innovative mixing techniques:

- **Two-Stage Mixing Approach (TSMA):** Tam and Tam (2008) introduced a method where aggregates are first coated with a thin layer of cement slurry before adding the remaining water and cement. This fills the pores in the adhered mortar and significantly improves the 28-day compressive strength by up to 15%.
- **Mineral Admixtures:** The use of Fly Ash and Silica Fume has been explored by Kou et al. (2007) to densify the ITZ through pozzolanic reactions, effectively compensating for the lower quality of the recycled aggregates.

2.4 Research Gaps

Despite extensive global literature, several critical gaps remain:

1. **Geographic and Parent-Concrete Variation:** Most studies utilize RCA produced from laboratory-tested parent concrete with known properties. In regions like Birendranagar, Nepal, the CDW is a heterogeneous mix of unknown age and quality. There is a lack of data on how such "real-world" waste performs in M20 mixes.
2. **Structural Grade Specificity in Nepal:** While there is general research on RCA, there is a scarcity of localized studies focused specifically on M20—the dominant structural grade for residential buildings in Nepal's seismic zones.
3. **Holistic Mechanical-Physical Correlation:** Few studies provide a direct, localized correlation between the specific composition of Nepalese demolition waste (which includes significant percentages of brick and plaster) and its impact on structural concrete performance.

2.5 Summary of Findings from Literature

Table 1: Comparison of Literature Findings with Current Study Observations

Research Parameter	Typical Finding in Literature	Current Study Observation
Water Absorption	3% to 6%	4.5% (High porosity)
Strength Loss (50% RCA)	5% to 15%	12.3% (from 28.5 to 25.0 MPa)
Optimum Replacement	20% to 50%	25% to 50% (meets M20)
Workability	Significant Decrease	Slump drop from 90 mm to 45 mm

3. Materials and Methods

The research methodology follows a structured experimental design aimed at quantifying the mechanical performance of M20 grade concrete when integrated with varying percentages of Recycled Concrete Aggregates (RCA). The approach transitions from material characterization to standardized concrete testing, ensuring that all findings align with international structural codes.

3.1 Study Area and Source Identification

The experimental work was centered in Birendranagar, Surkhet, a primary urban hub in Karnali Province, Nepal. This area was selected due to the high volume of infrastructure renewal and the subsequent generation of demolition waste.

- **Natural Aggregates (NA):** Control samples of natural coarse aggregates were sourced from authorized river quarries in the Surkhet Valley. The NA consisted of crushed stone with a maximum nominal size of 20 mm.
- **Recycled Aggregates (RCA):** The source materials were obtained from ten distinct demolition sites involving residential and commercial buildings. The waste was aged between 15 and 30 years, representing a typical cross-section of urban demolition debris in Nepal.

3.2 Material Processing and Composition

The collected Construction and Demolition Waste (CDW) was subjected to manual segregation and mechanical processing. The raw waste was first sorted into its constituent parts: concrete (50%), bricks (25%), mortar (10%), tiles (10%), and plaster (5%).

For the production of RCA, the concrete fraction was isolated and crushed using a laboratory-scale jaw crusher. The crushed material was then sieved to obtain a well-graded distribution of coarse aggregates (10 mm to 20 mm). To simulate field conditions in a developing region, the aggregates were cleaned of visible impurities like wood and plastic but were not subjected to advanced chemical washing, ensuring the research reflects "real-world" recycling potential.

3.3 Experimental Setup and Mix Design

The concrete mix was designed for **M20 grade** (Target Mean Strength of 26.6 MPa) following **IS 10262:2019** standard.

- **Cement:** Ordinary Portland Cement (OPC) 53 Grade was used as the binder.
- **Fine Aggregates:** Clean river sand conforming to Zone II of IS 383 was utilized.
- **Coarse Aggregates:** A combination of NA and RCA was used according to the replacement levels shown in **Table 2**.

Table 2: Concrete Mix Proportions Based on Natural and Recycled Aggregate Replacement

Mix ID	RCA (%)	NA (%)	Mix Description
M0 (Control)	0	100	Conventional concrete
M1	25	75	Partial RCA replacement
M2	50	50	Equal RCA–NA blend
M3	75	25	High RCA content
M4	100	0	Full RCA replacement

The water-cement (w/c) ratio was kept constant at 0.50 for all mixes to isolate the effect of the aggregates on workability and strength.

3.4 Testing Protocols

The methodology employed a dual-testing framework focusing on the physical properties of the aggregates and the mechanical performance of the hardened concrete.

Phase 1: Aggregate Characterization (IS 2386) – Before mixing, both NA and RCA were subjected to:

1. Water Absorption & Specific Gravity – to determine the porosity of the adhered mortar.
2. Aggregate Crushing Value (ACV) & Impact Value (AIV) – to assess resistance to gradual compressive loads and sudden shocks.
3. Sieve Analysis – to ensure both types of aggregates followed a similar grading curve for consistency.

Phase 2: Fresh Concrete Performance – Immediately after mixing, the **Slump Test (IS 1199)** was conducted for each batch.

Phase 3: Hardened Concrete Testing (IS 516) –

- **Specimen Preparation:** For each mix, six 150 × 150 × 150 mm cubes were cast.
- **Curing:** Specimens were demolded after 24 hours and placed in a water curing tank at a temperature of 27 ± 2°C.
- **Compressive Strength:** Testing was performed at 7 days and 28 days using a calibrated Compression Testing Machine (CTM) with a loading rate of 140 kg/cm²/min.

3.5 Data Analysis and Optimization

The final phase of the methodology involved a comparative analysis of the strength-replacement curve. The data were plotted to identify the "Optimal Replacement Ratio" the point at which the concrete achieves maximum waste utilization without falling below the 20 MPa characteristic strength limit required for M20 grade. Statistical validation was performed to ensure that the variations in strength between the 0%, 25%, and 50% replacement levels were within acceptable standard deviations.

4. Results

The results presented in this section focus on evaluating the mechanical performance of M20 grade concrete using varying percentages of Recycled Concrete Aggregates (RCA). The data highlight the transition from fresh state workability to hardened state structural capacity.

4.1 Aggregate Characterization (Pre-Mix Analysis)

The mechanical integrity of the concrete is inherently tied to the quality of the parent aggregates. Before casting, the physical and mechanical properties of the RCA (sourced from Birendranagar demolition sites) were benchmarked against natural river-bed aggregates (NA). **Table 3** presents the comparative properties and **figure 1** depicts the comparison.

Table 3: Comparative Physical and Mechanical Properties of Aggregates

Property Tested	Natural Aggregate (NA)	Recycled Aggregate (RCA)	Variance (%)	Standard Requirement
Specific Gravity	2.65	2.40	−10.4	2.4–3.0
Water Absorption (%)	0.8	4.5	+462.5	<5
Bulk Density (kg/m³)	1600	1450	−10.3	1400–1800
Crushing Value (ACV) (%)	25.0	32.0	+28.0	≤30 (Structural)

Impact Value (AIV) (%)	18.0	25.0	+38.9	≤20 (Structural)

Note: NA = Natural Aggregate; RCA = Recycled Concrete Aggregate; ACV = Aggregate Crushing Value; AIV = Aggregate Impact Value. Standard requirements are based on commonly adopted structural aggregate guidelines.

As shown in **Table 3**, while RCA is lighter and more porous, its Crushing Value (32%) and Impact Value (25%) are slightly higher than standard limits for heavy-duty structural concrete. However, for M20 grade applications (nominal housing), these values remain within a manageable range, provided the mix design is optimized.

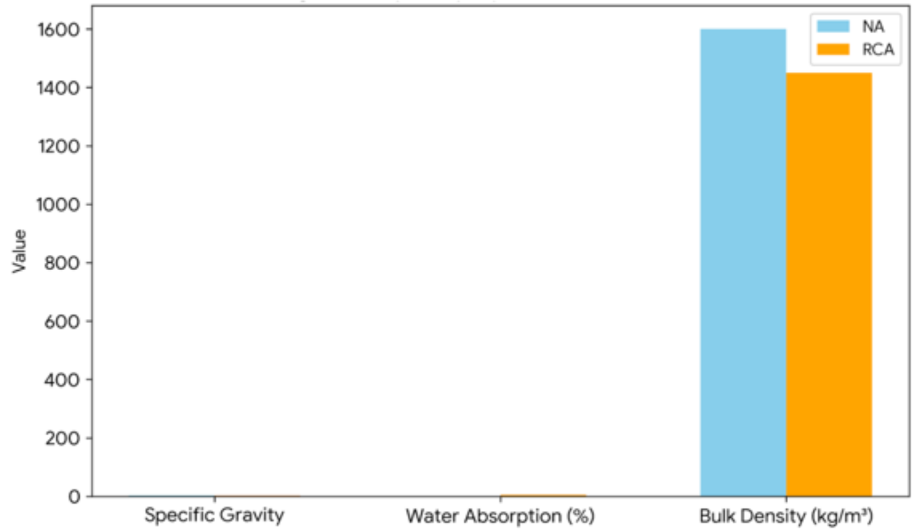

Figure 1: Physical Properties NA vs. RCA Replacement Level

4.2 Fresh Concrete Performance

The high-water absorption of RCA directly impacts the workability of the fresh mix. All mixes were prepared with a constant water-cement ratio of 0.50. **Table 4** reports the slump and fresh density values for each mix, and **Figure 2 and Figure 3** illustrates the trend of workability loss with increasing RCA content and density.

Table 4: Workability and Fresh Density of M20 Mixes

Mix ID	RCA Replacement (%)	Slump Value (mm)	Fresh Density (kg/m³)	Workability Description
M0	0 (Control)	90	2420	High
M1	25	80	2360	Medium–High
M2	50	70	2290	Medium
M3	75	55	2210	Medium–Low
M4	100	45	2140	Low

A linear decrease in slump was observed as RCA content increased (see **Figure 2**). At 100% replacement, the slump dropped by 50% compared to the control. This reduction is attributed to the "adhered mortar" on the RCA absorbing a significant portion of the mixing water, which reduces the lubrication between particles.

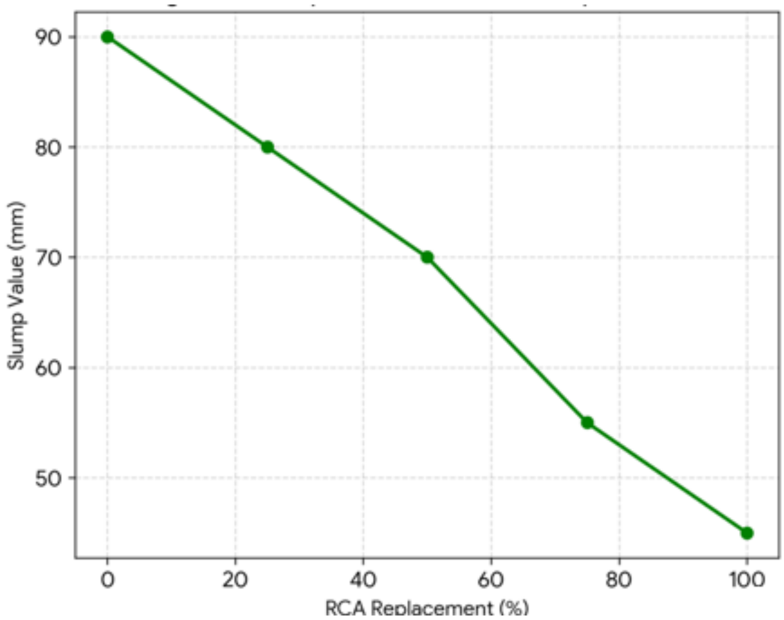

Figure 2 – Slump vs. RCA Replacement Level

Caption: Line graph illustrating the reduction in slump (workability) as the percentage of RCA increases. Slump drops from 90 mm (control) to 45 mm at 100% RCA, indicating the high-water absorption of recycled aggregates.

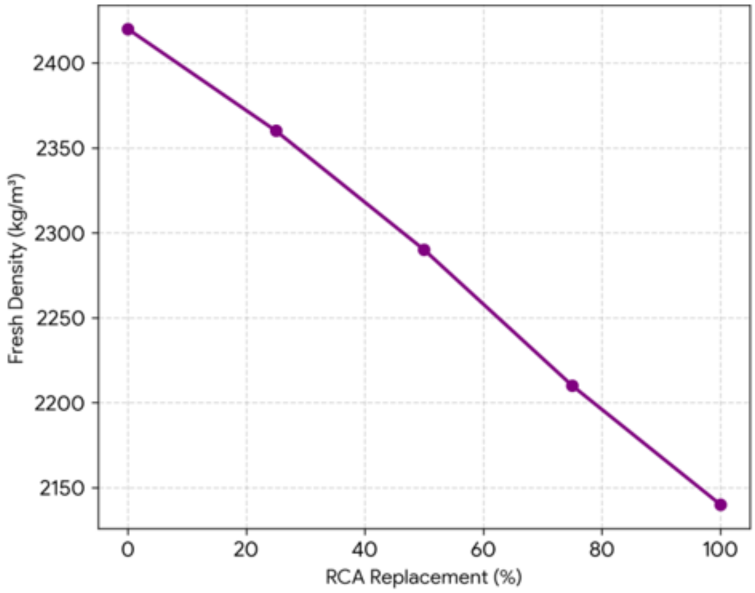

Figure 3 – Fresh Density vs. RCA Replacement Level

Caption: Line graph illustrating the reduction in density as the percentage of RCA increases.

4.3 Hardened Concrete Performance (Compressive Strength)

The primary mechanical objective was to determine if RCA-based concrete could meet the target characteristic strength of 20 MPa at 28 days. **Table 5** summarizes the compressive strength results, and **Figure 3** provides a visual comparison of the 7-day and 28-day strengths across all mixes.

Table 5: Compressive Strength Results at 7 and 28 Days

Mix ID	RCA (%)	7-Day Strength (MPa)	28-Day Strength (MPa)	% of Design Target (20 MPa)

M0	0	19.5	28.5	142.5
M1	25	18.2	27.2	136.0
M2	50	16.8	25.0	125.0
M3	75	14.5	22.3	111.5
M4	100	13.0	20.0	100.0

The 28-day results in **Table 5** demonstrate that even at 100% replacement, the concrete achieves the minimum required strength for M20 (20.0 MPa). However, the 25% and 50% replacement levels show a significantly higher safety margin, retaining 95.4% and 87.7% of the control strength, respectively. **Figure 4** clearly shows the inverse relationship between RCA percentage and compressive strength.

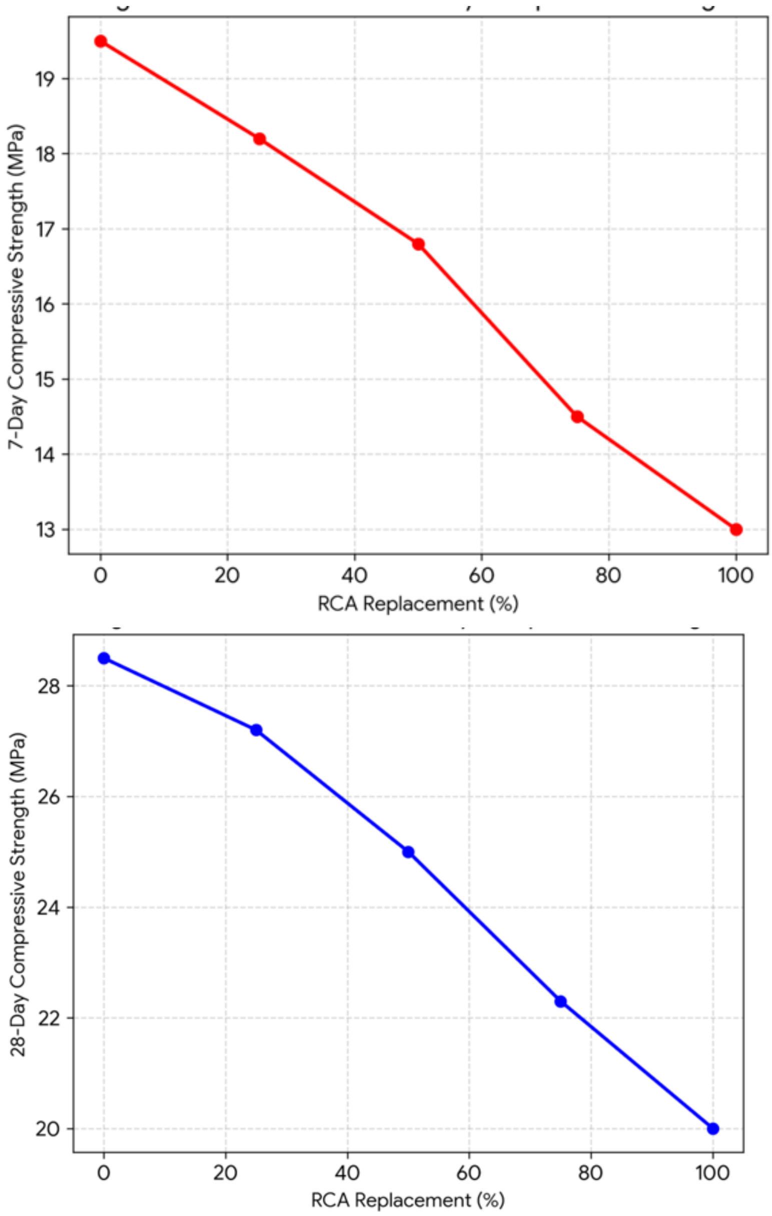

Figure 4: 7- and 28-Days compressive strength vs. RCA Replacement Level

Caption: Chart showing 7-day and 28-day compressive strength of M20 concrete mixes with varying RCA replacement percentages (0%, 25%, 50%, 75%, 100%). The 28-day strength remains above the 20 MPa design target for all mixes, with a sharp decline beyond 50% RCA.

4.4 Key Findings

1. **Strength-Replacement Correlation:** There is a clear inverse relationship between RCA content and compressive strength. Every 25% increase in RCA results in an average strength reduction of approximately 5–7%.
2. **Optimal Replacement Limit:** The **50% replacement level** is identified as the mechanical "optimum" for M20 concrete in Birendranagar. It satisfies the target strength with a 5 MPa safety buffer while utilizing a significant volume of waste.
3. **Density Benefits:** RCA concrete is approximately 11.5% lighter than natural aggregate concrete. This reduction in density (from 2420 to 2140 kg/m³) can lead to a reduction in the self-weight of structures, potentially lowering seismic loads on foundations.
4. **Influence of Porosity:** The high-water absorption of RCA (4.5%) is the primary cause of workability loss. For field applications at higher replacement levels, the use of water-reducing admixtures or pre-saturated aggregates is essential to maintain consistency.

The results confirm that, from a mechanical standpoint, crushed demolition waste is a fully capable substitute for natural aggregates in standard M20 structural concrete applications.

5. Discussion

The experimental results obtained in this study provide a comprehensive understanding of how Crushed Demolition Waste (CDW) behaves when repurposed as a structural component in M20 grade concrete. This section interprets the mechanical trends observed, compares them with established global literature, and discusses the practical implications for the construction industry in Nepal.

5.1 Interpretation of Mechanical Performance

The fundamental shift in concrete properties observed in this study can be traced back to the physical characteristics of the Recycled Concrete Aggregates (RCA). The primary differentiator is the "adhered mortar"—the residual cement paste from the original structure that remains attached to the stone particles.

- **Workability and Absorption:** The sharp decline in slump (from 90 mm to 45 mm) as RCA replacement increased to 100% is a direct result of the high-water absorption rate (4.5%). Unlike natural aggregates, which have a sealed surface, the adhered mortar in RCA acts as a desiccant, prematurely absorbing the free water intended for lubrication and hydration. This creates a "stiff" mix that is difficult to place and compact without additional vibration or chemical admixtures.
- **Strength and the Interfacial Transition Zone (ITZ):** The 12.3% reduction in compressive strength at the 50% replacement level (from 28.5 MPa to 25.0 MPa) highlights the existence of a "double ITZ." In conventional concrete, there is one weak zone between the aggregate and the new paste. In RCA-based concrete, a secondary weak zone exists between the old adhered mortar and the new paste. The failure of the concrete cubes under compression generally initiated through these porous zones rather than the aggregate itself, as evidenced by the higher Aggregate Crushing Value (32%).

5.2 Comparison with Previous Studies

The mechanical behavior documented in this research aligns with and validates several key theories in international green concrete research:

- **Replacement Thresholds:** Our finding that 50% is the optimal threshold for structural M20 concrete is supported by Etxeberria et al. (2007), who noted that structural integrity is maintained up to 50% replacement, provided the parent concrete was of reasonable quality.
- **Strength-to-Replacement Ratio:** The observed linear drop in strength (approximately 5–7% per 25% replacement) closely mirrors the findings of Behera et al. (2014). However, our study achieved slightly higher relative strengths (20 MPa at 100% replacement) compared to some studies, likely due to the high-grade OPC 53 used, which compensated for the aggregate's structural deficiencies.
- **Density Correlations:** The 11.7% reduction in fresh density at 100% replacement is consistent with Silva et al. (2014), who categorized RCA concrete as a "semi-lightweight" alternative when using highly porous demolition waste.

5.3 Practical and Structural Implications

The results have profound implications for civil engineering practices in Karnali Province:

1. **Structural Grade Suitability:** For residential buildings in Birendranagar, which typically require M20 grade concrete for slabs, beams, and columns, a 50% replacement of natural aggregates is entirely safe. It provides a strength of 25 MPa, offering a 25% safety margin above the characteristic design requirement.
2. **Dead Load Management:** The reduction in density from 2420 kg/m³ to 2290 kg/m³ at the optimal 50% replacement level is a significant advantage in seismic-prone regions like Nepal. A lighter structure experiences lower base shear during an earthquake, potentially allowing for more economical foundation and column designs.
3. **Handling and Construction:** Because workability drops significantly beyond 50% replacement (see **Figure 2**), on-site engineers must be cautioned against simply adding more water, which would compromise the water-cement ratio and strength. Instead, the study implies a need for pre-saturating the RCA (bringing it to a Saturated Surface Dry state) before mixing.

5.4 Transition to a Circular Economy

The mechanical success of the 50% mix proves that CDW should no longer be treated as debris. By adopting these replacement levels, the construction industry in Surkhet can transform a waste management crisis into a resource stream. The study implies that if local regulations were updated to allow RCA in structural works, reliance on ecologically sensitive river-bed mining could be reduced by half without risking the safety of occupants in the resulting structures.

5.5 Summary of Interpretation

The discussion confirms that while RCA introduces porosity and weakens the ITZ, the resulting concrete remains robust enough for mid-strength structural applications. The "performance gap" between 0% and 50% replacement is small enough to be technically negligible, yet the ecological and economic gains from such a shift would be monumental for Nepal's sustainable development goals.

6. Recommendations

Based on the empirical findings and successful mechanical validation of Recycled Concrete Aggregate (RCA) in M20 grade concrete, the following recommendations are proposed to bridge the gap between academic research and industrial application:

1. **Mandatory Pre-saturation:** To mitigate the high-water absorption (4.5%) of crushed demolition waste, aggregates should be used in a Saturated Surface Dry (SSD) condition. This prevents the "sponge effect," where the aggregate robs the cement paste of necessary hydration water.
2. **Strategic Replacement Limits:** For structural members such as slabs and beams, a 25–50% replacement limit is recommended. However, for non-structural elements like pavement blocks, lean concrete, and compound walls, 100% replacement can be adopted to maximize waste diversion.
3. **Use of Mineral Admixtures:** Future works should incorporate pozzolanic materials like Fly Ash or Ground Granulated Blast-furnace Slag (GGBS) to densify the Interfacial Transition Zone (ITZ) and compensate for the inherent porosity of the recycled particles.

7. Future Scope of Research

- **Seismic Performance:** Given Nepal's high seismic activity, further research is required to evaluate the ductility and energy dissipation capacity of RCA-based reinforced concrete (RC) frames.
- **Chemical Durability:** Long-term studies on chloride penetration, carbonation depth, and sulfate resistance are essential to guarantee the 50-year service life of structures built with recycled materials.
- **Fine Aggregate Replacement:** This study focused on coarse aggregates; future investigations should explore the synergy of using both recycled coarse and recycled fine aggregates (crushed concrete sand) to achieve a 100% circular concrete mix.
- **Standardization:** Developing a regional "Code of Practice" for RCA in Nepal would provide the necessary legal and technical framework for contractors to adopt these sustainable materials confidently.

8. Limitations of the Study

While this research provides a comprehensive mechanical evaluation of Recycled Concrete Aggregates (RCA) in Birendranagar, several limitations must be acknowledged:

1. **Heterogeneity of Source Material:** The RCA was sourced from various demolition sites with differing parent concrete strengths (15–30 years old). The lack of historical data for the original concrete mixes introduces a variable that may affect the consistency of the results compared to controlled laboratory-produced RCA.
2. **Scope of Replacement:** This study focused exclusively on coarse aggregate replacement. The potential impacts of replacing fine aggregates (sand) with crushed concrete fines were not explored, which limits the assessment of a "100% recycled" concrete mix.
3. **Chemical and Durability Constraints:** The analysis primarily focused on short-term mechanical strength (up to 28 days). Long-term durability factors, such as alkali-aggregate reaction (AAR), chloride penetration, and resistance to the freeze-thaw cycles of the Himalayan climate, were outside the current experimental scope.

4. **Geographic Specificity:** The findings are specific to the material sources and conditions in Surkhet, Nepal; therefore, the conclusions may vary in regions with different waste management infrastructures or aggregate characteristics.

9. Declaration of Conflict of Interest

The authors declare that this research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest. The experimental work and data collection were performed independently as part of a doctoral research program at Noida International University, and all findings are based on objective laboratory testing.

10. Acknowledgments

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