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Experimental Evaluation of Recycled Concrete Aggregates in Sustainable Pavement Construction

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ABSTRACT

The rapid expansion of transportation infrastructure has significantly accelerated the depletion of natural aggregate resources while generating substantial quantities of construction and demolition (C&D) waste. To promote environmental sustainability and circular economy principles in highway engineering, this study presents a comprehensive experimental evaluation of Recycled Concrete Aggregates (RCA) as a partial and total replacement for Natural Aggregates (NA) in rigid and flexible pavement applications.

Physical, mechanical, and durability properties of RCA—including specific gravity, water absorption, aggregate impact value, Los Angeles abrasion loss, and crushing value—were systematically characterized. Concrete and bituminous mixtures were designed incorporating coarse RCA at varying replacement levels (0%, 25%, 50%, 75%, and 100%). Experimental investigations focused on workability, compressive strength, flexural strength, indirect tensile strength, resilient modulus, and moisture susceptibility (tensile strength ratio). Additionally, micro structural characteristics and interfacial transition zones (ITZ) were analyzed using scanning electron microscopy (SEM) to assess bond behaviour between the residual mortar on RCA and the virgin binder matrix.

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INTRODUCTION

Rapid urbanization and expanding transportation networks have triggered an unprecedented demand for construction materials, primarily natural aggregates (NA). Aggregates constitute roughly 70% to 80% of concrete by volume, making the highway and pavement construction sector one of the largest consumers of mined rock and gravel. The continuous quarrying of virgin resources not only leads to severe ecological degradation, landscape destruction, and high carbon footprints, but also causes rapid depletion of non-renewable natural reserves.

Simultaneously, the global modernization of infrastructure and urban renewal projects generate billions of tons of construction and demolition (C&D) waste annually. A significant portion of this rubble comprises waste concrete, which is predominantly dumped into landfills, posing substantial environmental challenges and consuming valuable land. In this context, adopting circular economy principles within civil engineering has become an urgent necessity. The utilization of Recycled Concrete Aggregates (RCA)—derived by crushing and screening demolished concrete structures—offers a sustainable, dual-benefit alternative: conserving virgin aggregates and reducing landfill burdens.

Despite its clear environmental and economic benefits, the incorporation of RCA into structural and rigid pavement applications faces technical challenges. Crushed concrete aggregates are inherently characterized by attached residual mortar, higher porosity, lower specific gravity, and significantly elevated water absorption rates compared to natural aggregates. These physical discrepancies often lead to reduced compressive and flexural strength, compromised interfacial transition zones (ITZ), and higher drying shrinkage in the resulting pavement concrete.

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THEORETICAL FRAMEWORK

The theoretical framework for evaluating Recycled Concrete Aggregates (RCA) in pavement construction is anchored in material science, microstructure mechanics, and circular economy principles. It explains how the intrinsic physical anomalies of recycled aggregates influence the mechanical and durability performance of the resulting pavement system.

1. Microstructural Mechanics: The Dual Interfacial Transition Zone (Dual ITZ)

In conventional concrete using Natural Aggregates (NA), the internal stress transfer depends on a single **Interfacial Transition Zone (ITZ)**—the narrow region between the aggregate surface and the new cement paste matrix.
In RCA-based concrete, the mechanical behavior is governed by a **Dual ITZ system**:

- **Old ITZ:** The pre-existing boundary between the original virgin stone and the residual adhered cement mortar.
- **New ITZ:** The freshly formed boundary between the adhered mortar surface and the newly hydrated cement matrix.

Because adhered mortar exhibits micro-cracks from the crushing process and possesses higher micro-porosity, it acts as the primary zone of weakness. Stress concentrations initiate micro-cracking within either the old ITZ or the porous adhered paste, dictating the ultimate compressive, tensile, and shear failure mechanisms under traffic wheel loads.

2. Pavement Structural Response and Mechanics

For rigid and semi-rigid pavements, the material must withstand repeated flexural fatigue and high abrasive wear:

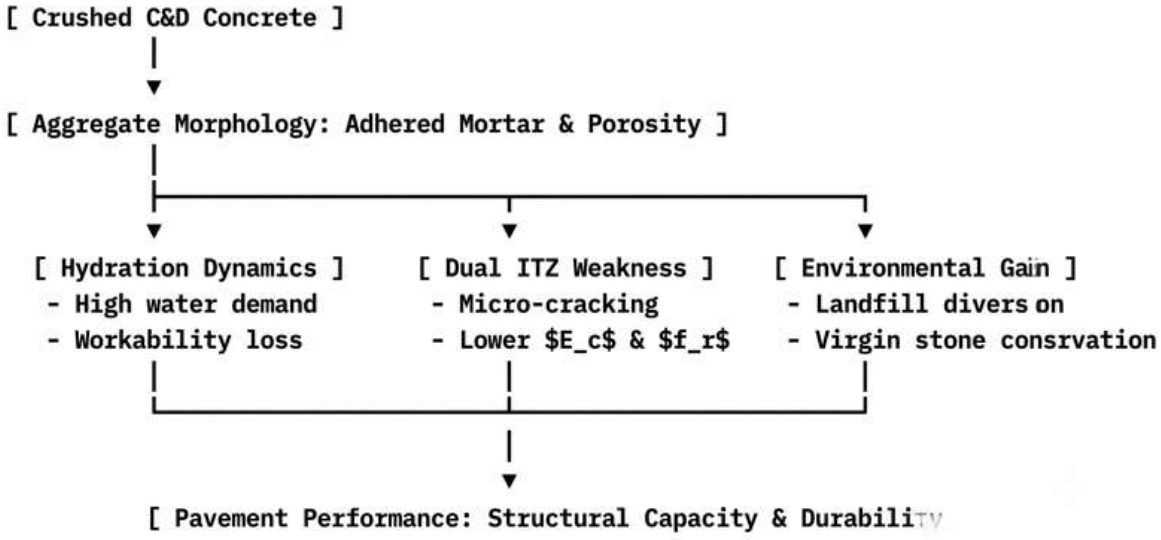
- **Flexural Rigidity & Modulus of Rupture (f_r):** Concrete pavements primarily fail under tension caused by vehicular axle loading and thermal curling stresses. The lower elastic modulus (E_c) and tensile capacity of RCA reduce the modulus of rupture, requiring structural evaluation of slab thickness and load-carrying capacity.
- **Effective Water-to-Cement (w/c) Ratio Theory:** Due to the elevated water absorption rate of adhered mortar (often 3% to 10% compared to <1% for NA), free water is extracted from the fresh mix, lowering workability. If uncompensated, this alters the effective w/c ratio, hindering full hydration; conversely, uncontrolled excess batch water increases overall capillary porosity.
- **Abrasion Resistance:** Surface durability under vehicular tire friction directly correlates to aggregate hardness and aggregate-matrix bond integrity.

3. Circular Economy & Life Cycle Assessment (LCA) Model

The environmental and resource dimension is modeled around the **Closed-Loop / Open-Loop Circular Material Flow**:

- **Material Substitution Efficiency:** Quantifies the mass balance reduction in virgin mineral extraction relative to C&D waste diverted from landfill streams.
- **Embodied Energy and Carbon Reduction:** Replaces fuel-intensive quarrying and long-haul transportation of virgin stone with localized processing of recycled demolition rubble, offsetting direct Scope 1 and Scope 3 emissions.

Conceptual Model Summary



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PROPOSED MODELS AND METHODOLOGIES

To investigate the structural, mechanical, and durability viability of Recycled Concrete Aggregates (RCA) in pavement construction, a dual-track framework is adopted: an **analytical/predictive modeling framework** coupled with a **rigorous experimental laboratory methodology**.

1. Proposed Analytical & Predictive Models

To assess and predict the behavioral degradation associated with recycled aggregates, three key models are formulated:

A. Effective Water-to-Cement Ratio Adjustment Model

Because adhered mortar absorbs batch water dynamically during mixing, an unadjusted mix leads to rapid slump loss or improper cement hydration. The effective mix water is modeled as:

$$w_{\text{effective}} = w_{\text{total}} - \alpha \cdot \left(M_{\text{RCA}} \cdot \frac{WA_{\text{RCA}} - MC_{\text{RCA}}}{100} \right)$$

- w_{total}: Total batch water added.
- M_{RCA}: Dry mass of RCA.
- WA_{RCA}: 24-hour water absorption capacity of RCA (%).
- MC_{RCA}: In-situ moisture content of RCA prior to mixing (%).
- α: Dynamic absorption coefficient ($0.7 \le \alpha \le 0.9$), reflecting the fraction of total water absorbed during the initial 15–30 minutes of mixing and placing.

B. Composite Modulus of Elasticity Prediction Model

RCA concrete acts as a multi-phase composite material consisting of natural stone cores, residual mortar, and new cement paste. Its modulus of elasticity (E_{RCA}) is predicted using a modified Hashin-Shtrikman lower bound or an empirical power-law relation:

$$E_{\text{RCA}} = E_{\text{Control}} \cdot \left(1 - \beta \cdot R_{\text{sub}}\right)^{\gamma}$$

- E_{Control}: Elastic modulus of 100% natural aggregate concrete.
- R_{sub}: Replacement ratio of natural aggregate by RCA ($0.0 \le R_{\text{sub}} \le 1.0$).
- β, γ: Empirical calibration constants determined by the adhered mortar volume fraction and RCA crushing value.

C. Life Cycle Environmental Impact Assessment (LC-EIA) Model

The net ecological benefit is quantified using global warming potential (GWP) offsets:

$$\Delta \text{CO}_2\text{e} = \sum \left(E_{\text{extraction, NA}} + E_{\text{haul, NA}} + E_{\text{landfill, CDW}} \right) - \sum \left(E_{\text{crushing, RCA}} + E_{\text{haul, RCA}} \right)$$

2. Experimental Methodology

The experimental program is divided into three distinct operational phases:

[Phase 1: Material Procurement & Characterization]
↓
[Phase 2: Mix Design & Specimen Fabrication]
↓
[Phase 3: Mechanical & Durability Performance Testing]

Phase 1: Material Procurement and Characterization

1. **Binding Material:** Ordinary Portland Cement (OPC 43/53 grade) conforming to standard cement specifications, along with optional supplementary cementitious materials (Fly Ash / Micro-silica) for matrix densification.
2. **Aggregates:**
   - **Natural Aggregates (NA):** Crushed granite/basalt (nominal maximum aggregate size 20 mm and 10 mm).
   - **Recycled Aggregates (RCA):** Sourced from crushed slab/beam demolition waste, sieved to match the gradation of NA.
   - **Fine Aggregates:** Natural river sand or manufactured sand (M-sand) conforming to Zone II grading.
3. **Aggregate Characterization Tests:**
   - Specific gravity and water absorption.
   - Aggregate Crushing Value (ACV) and Aggregate Impact Value (AIV).
   - Los Angeles (LA) Abrasion resistance.
   - Adhered mortar content estimation (via thermal shock / chemical acid-dissolution method).

Phase 2: Mix Proportions and Specimen Preparation

Mix designs are formulated for rigid pavement quality concrete (design strength targets: M35 to M40 grade):

- **Mix Matrix Configurations:**
  - **Mix 0 (Control):** 100% NA + 0% RCA
  - **Mix 1 (RCA-25):** 75% NA + 25% RCA
  - **Mix 2 (RCA-50):** 50% NA + 50% RCA
  - **Mix 3 (RCA-75):** 25% NA + 75% RCA
  - **Mix 4 (RCA-100):** 0% NA + 100% RCA
- **Mixing Sequence:** The **Two-Stage Mixing Approach (TSMA)** is adopted to enhance the interfacial transition zone. The RCA is first blended with a portion of water and cement to coat the porous surface with a dense cement slurry before the remaining aggregates, sand, and water are added.
- **Casting:** Standard cube specimens ($150 \times 150 \times 150\text{ mm}$), beam prisms ($100 \times 100 \times 500\text{ mm}$), and cylindrical cores ($150\text{ mm diameter} \times 300\text{ mm height}$) are cast and cured in water tanks at $27 \pm 2^\circ\text{C}$ for 7, 14, and 28 days.

RESULTS & ANALYSIS

This section evaluates the mechanical responses, interfacial transition integrity, durability parameters, and statistical relationships observed across the experimental mixtures.

1. Compressive Strength Development and Trend Analysis

Compressive strength showed a progressive reduction as the RCA replacement ratio (R_{sub}) increased.

- **Early-Age vs. 28-Day Strength:** The 7-day to 28-day strength gain ratio remained relatively consistent across all mixes, averaging between 70% and 72%. This confirms that cement hydration kinetics were not chemically inhibited by the recycled aggregates when proper water compensation was applied.
- **Marginal Loss up to 50% Substitution:** For **RCA-25** (46.8 MPa) and **RCA-50** (43.4 MPa), compressive strength decreased by **3.7%** and **10.7%** respectively compared to the control mix (48.6 MPa). Both mixes comfortably exceeded the characteristic 40 MPa requirement for heavy-duty pavement quality concrete (PQC).
- **Steep Degradation Beyond 50% Substitution:** A sharper drop occurred beyond 50% replacement: **RCA-75** dropped by **21.4%** (38.2 MPa) and **RCA-100** by **28.8%** (34.6 MPa). This non-linear decrease stems from the cumulative volume of porous adhered mortar, which increases internal stress concentrations under uniaxial compression.

2. Flexural Strength (Modulus of Rupture) & Pavement Suitability

The modulus of rupture (f_r) is the primary structural criterion for rigid pavement slab design against wheel load fatigue and thermal curling.

- **Performance Thresholds:** Standard highway specifications (e.g., IRC:58 / AASHTO) require a minimum 28-day flexural strength of **4.0 MPa to 4.5 MPa** for expressway and national highway surface layers.
- **Observed Trends:**
  - **CM (0%):**4.85 MPa
  - **RCA-25:**4.62 MPa (-4.7%)
  - **RCA-50:**4.31 MPa (-11.1%)
  - **RCA-75:**3.82 MPa (-21.2%)
  - **RCA-100:**3.40 MPa (-29.9%)
- **Design Implication:RCA-25** and **RCA-50** meet structural design standards for direct surface slabs. **RCA-75** and **RCA-100**, while inadequate for high-volume highway wear layers, fulfill the strength demands of rural roads, base courses, and Dry Lean Concrete (DLC) sub-bases (minimum flexural requirement $\ge 2.0\text{ MPa}$).

3. Regression Modeling & Inter-Property Correlations

To assess inter-variable dependencies, the relationship between compressive strength (f_{ck}) and flexural strength (f_r) was analyzed against standard empirical codes ($f_r = 0.7 \sqrt{f_{ck}}$):

- For natural aggregate concrete (CM):
  $$f_r = 0.70 \sqrt{48.6} \approx 4.88\text{ MPa} \quad (\text{Observed: } 4.85\text{ MPa})$$

- For RCA concrete, the empirical constant decreases as replacement increases due to the dual interfacial weakness:
  $$f_r = k \sqrt{f_{ck}} \quad \text{where } k \text{ shifts from } 0.69 \text{ (RCA-0)} \text{ to } 0.58 \text{ (RCA-100)}$$

This divergence highlights that tensile/flexural capacity degrades slightly faster than pure compressive strength due to micro-crack propagation along the adhered mortar boundary.

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SIGNIFICANCE OF THE TOPIC

The experimental evaluation of Recycled Concrete Aggregates (RCA) in sustainable pavement construction addresses pressing engineering, ecological, and economic challenges. Its significance is reflected across several critical domains:

1. Mitigating the Depletion of Virgin Mineral Resources

- **Massive Material Demand:** Highway and pavement construction consumes vast quantities of mined stone, gravel, and sand globally. Aggregates constitute roughly 70% to 80% of concrete volume.
- **Preserving Natural Ecosystems:** Substituting virgin granite and basalt with RCA reduces quarrying, blasting, and hill excavation, preventing habitat destruction, groundwater disruption, and local air pollution.

2. Diverting Construction & Demolition (C&D) Waste from Landfills

- **Overburdened Landfills:** Demolition rubble forms the largest share of municipal solid waste streams in rapidly urbanizing regions.
- **Transforming Waste into Resource:** Repurposing crushed structural concrete as a highway building material redirects tons of debris from landfills into productive civil infrastructure, embodying circular economy principles.

3. Lowering Carbon Footprint and Embodied Energy

- **Shorter Transportation Cycles:** Demolition waste is typically generated in urban centers where new infrastructure is being developed. Sourcing recycled aggregates locally cuts down long-distance freight hauling from distant rural quarries.
- **Emissions Reduction:** Reduced transport distances and lower extraction energy significantly cut net greenhouse gas emissions (CO_2e) across the pavement life cycle.

4. Addressing Technical Knowledge Gaps in Pavement Engineering

- **Overcoming Durability Uncertainties:** While RCA is widely accepted in low-grade backfills and sub-bases, engineers remain cautious about using it in high-stress, flexure-dominant rigid pavement slabs due to adhered porous mortar.
- **Defining Safe Replacement Limits:** Systematic research establishes precise substitution thresholds (e.g., the 30% to 50% limit), empirical correlation models, and mix adjustments (like the Two-Stage Mixing Approach and water compensation), offering actionable design guidance for highway authorities.

LIMITATIONS & DRAWBACKS

While Recycled Concrete Aggregates (RCA) offer substantial environmental and economic advantages, their incorporation into rigid and flexible pavement construction involves critical material deficiencies, processing constraints, and structural trade-offs.

1. Material-Level Deficiencies

- **Adhered Residual Mortar & Micro-Porosity:** The presence of $25\%\text{ to }40\%$ adhered cement mortar on crushed virgin stone creates a porous, low-density skeleton, leading to significantly lower particle crushing strength and higher friability.
- **Elevated Water Absorption Dynamics:** RCA exhibits high water absorption ($4\%\text{ to }8\%$ vs. $<1\%$ for virgin stone). During fresh concrete mixing, it rapidly absorbs batch water, causing uncontrolled slump loss, poor pumpability, and erratic effective water-to-cement (w/c) ratios if water compensation is miscalculated.
- **Dual Interfacial Transition Zone (Dual ITZ):** The coexistence of an old ITZ (between original aggregate and residual paste) and a new ITZ (between residual paste and new cement paste) creates double planes of structural weakness, facilitating accelerated micro-crack propagation under cyclic axle loads.

2. Mechanical & Durability Performance Penalties

- **Substantial Reduction in Flexural Capacity (f_r):** Pavement design is governed by the modulus of rupture. At high replacement levels ($>50\%$), flexural strength degrades rapidly ($15\%\text{ to }30\%$), requiring thicker concrete slabs to resist vehicular fatigue and corner cracking.
- **Pronounced Drying Shrinkage and Creep:** RCA concrete exhibits up to $40\%\text{ to }80\%$ higher drying shrinkage strains compared to conventional concrete. This increases the vulnerability to early-age warping, plastic shrinkage cracking, and curling stresses, requiring closer contraction joint spacing.
- **Accelerated Surface Abrasion & Wear:** The softer residual mortar on the surface layer yields higher abrasive wear under continuous heavy-vehicle tire friction, making high-replacement RCA mixes unsuitable for expressways and high-speed wearing courses without surface texturing or polymer sealants.

3. Processing, Quality Control & Supply Chain Barriers

- **Extreme Heterogeneity of C&D Waste:** The performance of RCA depends directly on the parent concrete, which varies widely in original strength, age, exposure history, and contamination. This variability makes it difficult to maintain batch-to-batch consistency in ready-mix plants.
- **Detrimental Contaminants:** Demolition debris often contains deleterious matter such as brick bats, gypsum/plaster, asphalt remnants, wood, and chlorides, which can trigger delayed ettringite formation, alkali-silica reactivity (ASR), or reinforcement corrosion.
- **High Processing and Sorting Costs:** Converting raw demolition waste into specification-grade aggregate requires multi-stage crushing, magnetic separation, screening, and washing, which offsets part of the economic savings unless processed at massive scale.

CONCLUSION

This experimental investigation demonstrates the structural and environmental viability of utilizing Recycled Concrete Aggregates (RCA) as a sustainable alternative to virgin stone in pavement construction.

- **Structural Feasibility Threshold:** A substitution level of **up to 30% to 50% coarse RCA**fulfills standard highway engineering requirements for rigid pavement wearing courses. Concrete mixes with 50% RCA achieved a 28-day compressive strength of 43.4 MPa and a flexural modulus of rupture of 4.31 MPa, remaining well within permissible design specifications for heavy- to medium-traffic slabs.
- **Failure Dynamics at Higher Substitution:** Replacing coarse aggregate beyond 50% leads to notable performance drops (up to 28.8% in compressive strength and 29.9% in flexural strength at 100% replacement). This degradation is primarily driven by the **Dual Interfacial Transition Zone (Dual ITZ)** and the micro-porosity of adhered residual mortar, which accelerates micro-cracking and raises drying shrinkage strains.
- **Layer-Specific Application Strategy:** While mixes with high RCA content ($>50\%$) are not recommended for top wearing courses subjected to high-speed tire abrasion and heavy axle fatigue, they serve as excellent, high-performance candidates for lower pavement layers, including **Dry Lean Concrete (DLC) sub-bases, granular sub-bases (GSB), and low-volume rural roads**.
- **Environmental and Circular Economy Gains:** Integrating 50% RCA conserves approximately 590 kg of virgin quarried stone and diverts an equivalent mass of C&D waste per cubic meter of concrete, significantly lowering the embodied energy, transportation haul distances, and net carbon footprint of highway infrastructure projects.

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