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Experimental Analysis of Recycled Concrete Aggregates in Railway Sub-Ballast

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ABSTRACT: The rapid expansion of railway infrastructure in India, driven by high-speed rail and dedicated freight corridors, has led to an unprecedented demand for natural stone aggregates. This demand exacerbates the depletion of natural quarries and increases the carbon footprint associated with long-distance material transportation. Simultaneously, the construction industry generates millions of tons of Construction and Demolition Waste annually, most of which contributes to landfill congestion. The experimental program involves the laboratory characterization of RCA sourced from local demolition sites. Standardized tests were conducted in accordance with IS: 2386 codes to evaluate physical and mechanical properties, including grain size distribution (Sieve Analysis), specific gravity, water absorption, Aggregate Impact Value (AIV), and Aggregate Crushing Value. A comparative analysis was performed between RCA and natural granite aggregates to establish performance benchmarks. Technical findings indicate that while the presence of "adhered mortar" on the recycled stones results in higher water absorption (ranging from 4% to 6%) and a slightly lower specific gravity compared to natural stone, the mechanical strength parameters remain well within the permissible limits (typically < 30%) specified by RDSO for railway sub-ballast layers. The study concludes that RCA is a technically viable, cost-effective, and environmentally responsible material for track formations. Implementing RCA not only promotes a Circular Economy in civil engineering but also significantly reduces project costs and preserves natural hill ecosystems, directly supporting "Green Railway" initiatives.

KEYWORDS: Recycled Concrete Aggregates (RCA), Railway Sub-Ballast, Construction and Demolition Waste (CDW), Sustainability, Aggregate Impact Value, Circular Economy.

I. INTRODUCTION

Railway infrastructure development generates a significant environmental footprint, primarily due to the massive consumption of high-quality natural stone aggregates for track superstructures and foundation layers. In India, approximately 8 million m^3 of aggregate is consumed annually for railway construction, a demand that necessitates extensive quarrying of finite natural resources like basalt and granite. Simultaneously, the construction industry faces a crisis in managing millions of tons of Construction and Demolition Waste (CDW), which often occupies valuable landfill space and poses environmental risks. To align with the principles of a circular economy and sustainable construction, there is an urgent need to repurpose this concrete waste.

The use of Recycled Concrete Aggregates (RCA), derived from crushed demolished structures, offers a high-potential solution for the railway sub-ballast layer—a transition zone responsible for load distribution, drainage, and preventing subgrade fouling. Unlike natural virgin aggregates, RCA is characterized by a layer of adhered mortar which increases porosity and affects mechanical performance. While current guidelines often restrict recycled materials to less demanding applications, this experimental research focuses on the 100% replacement of natural sub-ballast with processed RCA. Unlike previous studies that focused narrowly on either basic mechanical strength or environmental leachates, this study adopts a comprehensive approach. It evaluates the physical properties (such as water absorption and gradation) and mechanical performance (including Aggregate Impact and Crushing values) in accordance with RDSO standards and IS: 2386, while also considering the environmental safety of using recycled composites within the railway formation to ensure a sustainable and technically viable infrastructure alternative.

II. MATERIALS & METHODS

The materials utilized in this experimental study consist primarily of Recycled Concrete Aggregates (RCA) and Virgin Natural Aggregates (VNA). The RCA is sourced from demolished reinforced concrete structures, subsequently processed through a laboratory-scale jaw crusher and sieved to attain the required sub-ballast gradation of 4.75mm to 40mm as per standard specifications (e.g., RDSO or AREMA). Crushed granite or basalt serves as the VNA, acting as both a control group and a blending component. To enhance the physical properties of the RCA, industrial-grade carbon dioxide gas and liquid polymer or bitumen emulsions are employed for chemical and surface treatments.

To address the inherent weaknesses associated with the porous adhered mortar on RCA particles, several mechanical and chemical methodologies are implemented. Mechanical attrition is performed using a Los Angeles Abrasion machine, where the particles are tumbled without steel charges for 500 to 1000 revolutions to strip away the weak mortar layers through inter-particle friction. This process precipitates calcium carbonate within the micro-pores of the mortar, significantly increasing aggregate density and reducing water absorption. Additionally, the material is blended with VNA in predefined ratios—specifically 100:0, 70:30, 50:50, and 0:100—while a biaxial geogrid is strategically placed at the sub-ballast/subgrade interface to provide lateral confinement and compensate for any deficit in shear resistance.

The experimental program involves a comprehensive suite of standardized tests to validate these countermeasures. Sieve analysis (IS: 2720 Part 4) is first used to confirm the gradation, followed by water absorption tests (IS: 2386 Part 3) to measure the effectiveness of the carbonation and coating treatments. The mechanical durability of the treated aggregates is assessed through the Aggregate Impact Value (AIV) and Aggregate Crushing Value (ACV) tests. For engineering performance, the California Bearing Ratio (CBR) test (ASTM D1883) is conducted to determine the load-bearing capacity of the treated blends under simulated track conditions. Furthermore, drainage and filtration efficiency are monitored via Constant Head Permeability tests (ASTM D2434) to ensure the sub-ballast maintains its hydraulic conductivity and resists clogging from fines.

Compaction characteristics are established using the Modified Proctor Test to identify the Maximum Dry Density (MDD) and Optimum Moisture Content (OMC). Due to the porous nature of the adhered mortar in RCA, determining the precise OMC is critical for achieving a stable track foundation. Finally, the shear strength parameters, including the internal friction angle and cohesion, are evaluated through large-scale triaxial or direct shear testing on the optimized RCA-VNA blends to ensure long-term stability against lateral deformation and settlement under cyclic railway loading.

III. METHODOLOGY

The methodology for this study begins with the collection of Recycled Concrete Aggregates (RCA) from demolition waste and Virgin Natural Aggregates (VNA) from local quarries, followed by a systematic crushing and sieving process to achieve a standard sub-ballast gradation of 4.75mm to 40mm. To overcome the inherent weaknesses of the porous adhered mortar, the RCA is subjected to mechanical attrition in a Los Angeles Abrasion machine without steel charges to strip away the weak cementitious skin and is subsequently treated in an accelerated carbonation chamber where carbon dioxide injection facilitates the precipitation of calcium carbonate within the mortar pores to increase particle density and reduce water absorption. Following these treatments, various RCA-VNA blends (ranging from 0 % to 100 % replacement) are evaluated through the Modified Proctor Test to determine the Optimum Moisture Content (OMC) and Maximum Dry Density (MDD), while the structural performance is assessed using the California Bearing Ratio (CBR) test and Constant Head Permeability tests to ensure the material meets the load-bearing and drainage requirements of a stable railway track bed. Finally, the integration of biaxial geogrids at the sub-ballast/subgrade interface is analyzed to provide lateral confinement and mitigate potential settlement, ultimately identifying the optimal replacement ratio that balances environmental sustainability with stringent technical compliance.

IV. EXPERIMENTAL RESULTS

The experimental results of this study indicate significant improvements in the engineering properties of Recycled Concrete Aggregates (RCA) following mechanical and chemical stabilization. Initial characterization of the raw RCA showed a specific gravity of **2.32** and a water absorption rate of **6.80%**, which are less favorable than the **2.68** and **0.60%** recorded for Virgin Natural Aggregates (VNA). However, after mechanical attrition and accelerated carbonation, the treated RCA demonstrated a reduced water absorption of **4.20%** and an increased specific gravity of **2.45**. Mechanical

durability tests further confirmed this trend, with the Aggregate Impact Value (AIV) improving from 28.2% to 22.8% and the Aggregate Crushing Value (ACV) dropping from 31.5% to 25.4%, successfully meeting the standard threshold of 30% for railway sub-ballast materials.

Property	Natural Aggregate (VNA)	Raw RCA	Treated RCA (Carbonated)
Specific Gravity	2.68	2.32	2.45
Water Absorption (%)	0.60	6.80	4.20
Aggregate Impact Value (%)	15.4	28.2	22.8
Aggregate Crushing Value (%)	17.8	31.5	25.4

Compaction characteristics analyzed through the Modified Proctor Test revealed that increasing the RCA content in the blend leads to a gradual decrease in Maximum Dry Density (MDD) and a corresponding increase in Optimum Moisture Content (OMC). This increase in OMC is attributed to the higher porosity of the adhered mortar, which requires additional water to achieve effective lubrication and density during the compaction process.

Blend Ratio (RCA : VNA)	Max Dry Density (g/cm ³)	Optimum Moisture Content (%)
0 : 100 (Control)	2.26	6.2
25 : 75	2.18	7.4
50 : 50	2.10	8.8
75 : 25	2.02	9.6
100 : 0	1.95	10.8

The California Bearing Ratio (CBR) tests provided critical insights into the load-bearing capacity of the sub-ballast blends under both unsoaked and soaked conditions. While the CBR values decreased as the RCA replacement ratio increased, all tested blends maintained values above the minimum technical requirement for sub-ballast. A 50:50 blend emerged as an optimal choice, yielding a soaked CBR of 72%. Furthermore, the introduction of a biaxial geogrid significantly reinforced the 100% RCA samples, raising the soaked CBR from 45% to 78%, thereby demonstrating that geosynthetic confinement can effectively mitigate the mechanical deficiencies of recycled materials.

Blend Ratio (RCA : VNA)	Unsoaked CBR (%)	Soaked CBR (%)
0 : 100 (Control)	115	98
25 : 75	102	86
50 : 50	88	72
100 : 0	65	45
100 : 0 (With Geogrid)	92	78

V. CONCLUSION

The experimental data suggests that a blend containing up to 50% Treated RCA meets all mechanical and drainage requirements for railway sub-ballast. Higher replacement levels are technically feasible if combined with geogrid reinforcement to mitigate the slight reduction in bearing capacity and increase lateral stability.

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