iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH
IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 13 Issue: IX Month of publication: September 2025

DOI: https://doi.org/10.22214/ijraset.2025.74210

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 13 Issue IX Sep 2025- Available at www.ijraset.com

Sustainability Assessment and Performance Evaluation of Recyclable and Modular Concrete Incorporating Treated Recycled Fine Aggregates

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Abstract: This study presents a comprehensive sustainability assessment of Recyclable and Modular (R&M) Concrete incorporating treated Recycled Fine Aggregates (RFAs) derived from Construction and Demolition Waste (CDW). While conventional concrete remains a structurally reliable material, its dependence on virgin sand, high embodied energy, and associated CO_2 emissions make it environmentally and economically unsustainable in the long term. To address these challenges, this research evaluates the economic, environmental, and socio-technical feasibility of replacing natural sand with RFAs at varying levels (0%, 30%, 50%, and 100%). The assessment integrates direct material cost analysis, life cycle economic indicators, embodied carbon quantification, and socio-economic evaluation to provide a holistic understanding of R&M concrete's viability. Experimental findings reveal that 30–40% RFA replacement delivers the optimal balance, achieving 10–15% cost savings per cubic meter, along with 11–17% reductions in embodied CO_2 emissions, 35% conservation of natural resources, and up to 45% landfill diversion. Additionally, the study highlights social co-benefits, including employment generation in CDW recycling supply chains and enhanced affordability for prefabricated modular applications. Although higher replacement levels (≥50%) negatively influenced mechanical performance and durability, pre-treatment techniques improved material quality and extended usability within structural-grade applications. Overall, the research demonstrates that R&M concrete, when optimized with treated RFAs, represents a technically sound, eco-efficient, and economically viable construction material. Its integration into modular construction systems offers a scalable pathway for advancing circular economy practices, resource efficiency, and sustainable infrastructure development.

Keywords: Recycled Fine Aggregates (RFA); Sustainability Assessment; Modular Concrete; Construction and Demolition Waste (CDW); Sustainable Construction.

I. INTRODUCTION

Concrete is the most widely used construction material globally, with an annual production exceeding 30 billion tons (Yao & Hong, 2024). While its widespread application has enabled significant advancements in infrastructure, it also presents substantial environmental and structural challenges. Conventional concrete exhibits limited tensile strength, susceptibility to structural defects, and reduced durability when exposed to environmental stressors (Sandanayake et al., 2020a). Researchers have explored alternative materials and innovative techniques to enhance concrete properties in response to these drawbacks.

Recent studies have highlighted the potential of supplementary materials, such as recycled and modular concrete, to boost sustainability and efficiency in construction. Recycled concrete, made from demolished structures, decreases reliance on virgin materials and reduces waste, supporting a circular economy. Similarly, modular concrete, with its prefabricated and reusable components, makes construction faster, cuts down on-site waste, and lowers carbon emissions. These innovations align with global sustainability goals and address economic and social factors, including cost savings, job creation, and long-lasting infrastructure.

Recycled and modular concrete exhibits notable advantages in terms of mechanical properties, environmental impact, and economic viability. Studies suggest that optimized mixtures incorporating recycled aggregates and modular designs enhance structural integrity by improving density, reducing porosity, and mitigating crack propagation (Wattanapanich et al., 2024). Additionally, these materials demonstrate superior durability against water infiltration, chloride penetration, and freeze-thaw cycles, making them suitable for resilient infrastructure projects (Wang et al., 2022). However, widespread adoption faces material variability, standardization, and cost-effectiveness challenges.

The escalating global demand for construction materials, particularly concrete and mortar, has placed unprecedented pressure on natural resource reserves (Zhong et al., 2022). Traditional construction practices rely extensively on non-renewable materials such as river sand, limestone, and natural aggregate resources that are depleted at unsustainable rates. Projections indicating a doubling of concrete consumption by 2050 further exacerbate this concern, highlighting a critical need for sustainable material alternatives to support future infrastructure growth (Sivashanmugam et al., 2022). Simultaneously, the construction sector generates substantial volumes of Construction and Demolition Waste (CDW), much of which is either landfilled or left unmanaged, contributing to environmental degradation and inefficient resource utilization. Figure 1 depicts the bulk volume, machinery involvement, and resource depletion in construction waste management.

Figure 1: Overview of Construction and Demolition Waste

Despite increasing awareness among urban stakeholders regarding the resource potential embedded in CDW, actual deployment of recycling practices remains constrained by technological limitations**,** lack of standardized processing protocols**,** insufficient policy enforcement, and skepticism from construction professionals regarding the structural reliability of recycled materials. This study aims to bridge these gaps by establishing a technical framework for the systematic treatment, characterization, and performance validation of RFAs, while aligning the material lifecycle with sustainability goals.

By adapting global best practices to India's specific socio-economic and environmental context, this research contributes toward reducing landfill dependency, conserving natural resources, minimizing embodied carbon, and advancing the engineering of recyclable and modular concrete technologies.

II. SUSTAINABILITY ANALYSIS OF RECYCLED AND MODULAR CONCRETE

The sustainability analysis of concrete and mortar prepared with recycled fines and the implications of utilizing recycled materials in construction require efficient evaluations of the sustainability and economic viability of the proposed approach, considering factors such as resource conservation and environmental impact (Bharadwaj et al., 2025). The benefits and challenges of using recycled aggregates in construction and recommendations for future research and practice are provided.

Reutilizing CDW in concrete and mortar to fulfill the demand for natural resources offers a sustainable means of meeting the sheer volume of required materials (Debbarma et al., 2024; Panghal & Kumar, 2024a). It addresses disposal issues by effectively removing waste from the waste stream. The strategic utilization of recycled fine aggregate (RFA) obtained from CDW recycling in the construction industry emerges as a paramount solution capable of concurrently ameliorating issues about the imbalance of river ecosystems, air pollution, and waste management (Blengini & Garbarino, 2010).

The advantages of using Recycled and Modular Concrete are as follows:

1) Economic, as it is available at low cost
2) Sustainable, as the material is reused
3) Social benefits – decrease debris and waste that remain unattended
4) Locally available at low cost
5) It has the potential to do more than fill material as per the literature
6) Inert material, so no chemical reaction and less reactive

7) Requires less treatment than other alternative
8) Decrease the cost of treatment of solid waste management
9) Save valuable land by stopping illegal dumping

Construction and building waste disposed of in landfills takes millions of years to decompose; thus, efficient strategies and facilities must be designed to handle and recycle waste. However, by following the experiences of other countries and following proper CDW processing, commercial recycling can be achieved.

III. LITERATURE REVIEW

The integration of Recycled Fine Aggregates (RF) derived from Construction and Demolition Waste (CDW) into concrete mixtures presents both opportunities and challenges for advancing recyclable and modular construction (R&M Concrete) (Vijayan et al., 2023). While RF enables the conservation of natural resources and supports circular construction principles, its incorporation significantly influences concrete's freshness, durability, and strength properties (Saiz Martínez et al., 2023). Key concerns include excessive water absorption due to the porous nature of RF, the presence of adhered mortar, which diminishes workability, and the formation of weakened interfacial transition zones (ITZ), all of which adversely impact mechanical performance. Moreover, contamination from chlorides, sulphates, and other residual chemicals further compromises the long-term durability of concrete incorporating RF (J. Wu et al., 2025). This study is strategically positioned to address the critical knowledge and implementation gap surrounding the utilization of Recycled Fine Aggregates (RFAs) in structural-grade concrete, with a specific focus on their application within Recyclable and Modular (R&M) Concrete systems. By undertaking a comprehensive experimental investigation, the research explores the influence of RFA incorporation on key performance domains namely, fresh properties (such as workability and setting time), mechanical behaviour (including compressive, tensile, and flexural strength), and durability performance (measured through water absorption, chloride ion penetration, and freeze-thaw resistance). These performance parameters are evaluated across varying replacement levels and treatment conditions, reflecting real-world construction scenarios. In doing so, the study addresses technical concerns widely reported in the literature, including the high-water absorption, poor interfacial transition zones, and contaminant-induced degradation associated with untreated RFAs (Kaptan et al., 2024). Moreover, it builds upon recent efforts by researchers such as (Sandanayake et al., 2020b), who demonstrated that targeted pre-treatment strategies such as acid washing, thermal processing, and pre-saturation can significantly improve the compatibility and performance of recycled aggregates in concrete. The scope of this research extends beyond mere laboratory validation. It aims to contribute toward the design of performance-based specifications and context-specific treatment frameworks for CDW-derived materials, thereby enabling their broader adoption in mainstream infrastructure projects. By generating empirical data on performance trends and trade-offs, the study supports decision-making for material engineers, sustainability practitioners, and policymakers.

A. *Mechanical, Durability Performance, and Structural Integrity*

The mechanical performance of concrete incorporating RFA is closely linked to the integrity of the *Interfacial Transition Zone (ITZ),* the weakest microstructural region in the concrete matrix (Eamon et al., 2021). The introduction of RFA affects strength development due to:

1) Weakened ITZs: The high porosity and microcracks in adhered mortar facilitate stress concentration and early crack initiation.
2) Strength reduction: Compressive strength reductions of 10–30% have been observed at complete RFA replacement levels (Sawab et al., 2016). Though optimized treatments and mix designs can mitigate losses.
3) Tensile and flexural performance: Limited bond strength and poor aggregate interlocking result in lower tensile and flexural capacities, critical in prefabricated and modular units subjected to dynamic loads. However, research (Panghal & Kumar, 2024b) suggests that including pozzolanic materials (e.g., fly ash, silica fume) can refine pore structure and improve the mechanical resilience of RFA-concrete mixes. Durability governs the life-cycle viability of concrete, especially in modular elements designed for reuse (Rajhans et al., 2018). Concrete made with RFA presents several durability challenges:
4) Increased permeability: Open pore structures in RFA increase water ingress, promoting freeze-thaw degradation and chloride ion diffusion.
5) Chemical durability risks: Sulfate attack, alkali-silica reaction (ASR), and leaching of contaminants are more pronounced in RFA mixes, particularly when CDW contains deleterious compounds (K. Wu, 2014).
6) Carbonation and corrosion potential: Accelerated carbonation rates due to low matrix density, combined with residual chlorides, pose a significant risk to steel reinforcement embedded in RFA-based concrete (Rajhans et al., 2018).

These issues underscore the need for performance-based durability assessments and possibly new durability indices specific to recycled aggregate concrete in structural applications.

B. Impact of Recyclable and Modular Construction

1) Environmental Impact of Conventional Concrete: Conventional concrete production significantly contributes to environmental degradation, with cement manufacturing alone responsible for approximately 8% of global CO2 emissions (Kasperzak et al., 2023). Extracting raw materials, energy-intensive production processes, and waste disposal further exacerbate sustainability concerns. Consequently, researchers have investigated alternative materials and methodologies to mitigate these adverse effects.
2) The Role of Recycled Concrete in Sustainable Construction: Recycled concrete aggregates (RCA) have emerged as a viable solution to reduce construction waste and minimize the environmental footprint of concrete production (Sharma & Trivedi, 2022). Studies indicate that RCA can replace natural aggregates without significantly compromising mechanical performance when optimized mix designs are employed. Using RCA also reduces landfill waste and conserves natural resources, aligning with circular economy principles (Behera et al., 2024).

Socio-Economic Implications of Sustainable Concrete Solutions: Adopting recycled and modular concrete has significant socio-economic benefits, including cost reductions, job creation, and resource efficiency. By repurposing demolition waste, construction projects can lower material costs and promote local recycling industries *(Victar & Waidyasekara, 2024)*. Additionally, modular construction techniques contribute to labour efficiency, reducing project timelines and associated expenditures *(Guo & Song, 2025)*.

IV. MATERIALS AND METHODOLOGY

The research employs a structured experimental methodology to evaluate the performance of Recyclable and Modular (R&M) Concrete incorporating treated Recycled Fine Aggregates (RFAs) and Recycled Coarse Aggregates (RCAs) sourced from processed C&D waste. The program was designed to align with IS and ASTM standards and consisted of six phases:

1) Raw material collection and characterization,
2) RFA treatment and verification,
3) Mix design formulation,
4) Specimen casting and curing,
5) Evaluation of fresh, mechanical, and durability properties, and
6) Comparative performance analysis against control mixes.

A. Materials

Ordinary Portland Cement (OPC 53 grade) conforming to IS 12269:1987 was used as the binding material (Figures 2–3). Its chemical composition is given in **Table 1**. Potable water meeting IS standards was used for mixing and curing. Natural river sand (Zone I, IS 383:2016) served as the reference fine aggregate, while RCA (10 mm and 20 mm) was derived from pre-processed C&D waste (Figure 4). RFA was sourced from crushed CDW fines containing mortar residue and plaster particles (Figure 5). Aggregates were tested for grading, specific gravity, fineness modulus, water absorption, and strength indices as per IS 2386 and IS 383. All materials were batched using a digital batching machine and mixed in a mechanical pan mixer (Figures 6a–6b) to ensure uniformity.

Table 1. Composition of OPC (Source: Manufacturer)

Constituent	%	Remarks
Lime (CaO)	62–69	Strength excess may cause unsoundness
Silica (SiO_2)	16–23	Strength development
Alumina (Al_2O_3)	2–6	Quick setting
Iron Oxide (Fe_2O_3)	0.4–3	Hardness and color
MgO	<5	Excess may cause unsoundness
LOI	<3	Moisture/volatile content
Chloride	<0.1	Limits corrosion
LSF	0.70–0.94	Ensures lime balance

B. Treatment of Recycled Fine Aggregates (RFA)

To mitigate the drawbacks of RFAs, such as high porosity and adhered mortar, multiple treatments were applied: water washing, acid soaking (HCl/H_2SO_4), thermal treatment, and pre-soaking. Post-treatment characterization confirmed improvements in density, water absorption, and cleanliness, ensuring conformity to IS 383:2016.

C. Mix Proportioning and Casting

Concrete mixes were prepared with 0%, 25%, 50%, 75%, and 100% RFA replacement levels following IS 10262:2019 for M30 and M40 grades. Superplasticizers were added to maintain workability. Specimens were cast using steel moulds for cubes (150×150×150 mm), cylinders (100×200 mm), and beams (100×100×500 mm), and cured under controlled conditions (Figure 2).

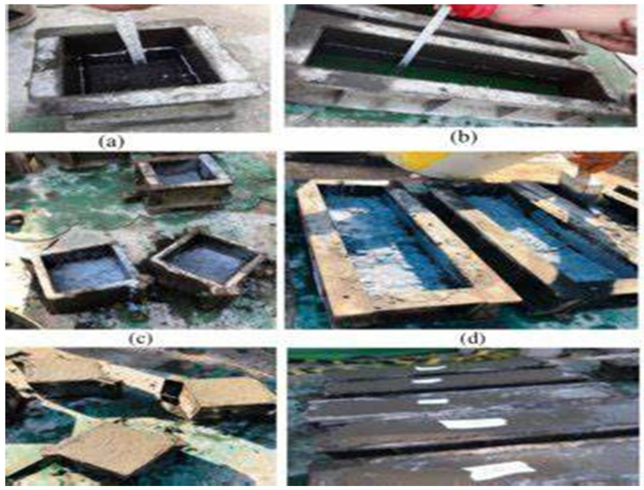

Figure 2: Mould Specimen used for Experiments

For modular evaluation, standardized blocks (400×200×200 mm) and panels (500×500×100 mm) were cast, simulating practical prefabrication applications. Dimensional precision was ensured via vibration compaction and steel moulds.

D. Testing Protocols

1) Fresh Properties: Workability and flowability assessed using the slump test (IS 1199:1959) as shown in Figure 3.

Figure 3: Slump Test

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Volume 13 Issue IX Sep 2025- Available at www.ijraset.com

2) Mechanical Properties: Compressive strength (7, 28, 56 days, IS 516:1959), split tensile (IS 5816:1999), and flexural strength under third-point loading (IS 516:1959) (Figures 4-6).



Figure 4: Compressive Strength Test Figure 5: Split Tensile Strength Test Figure 6: Flexural Strength Test

3) Durability Properties: Water absorption (IS 2386 Part 3), Rapid Chloride Penetration Test (ASTM C1202), and sulphate resistance via Na_2SO_4 immersion (ASTM standards). Freeze-thaw cycles were additionally performed for durability verification, as shown in Figure 7.

Figure 7: Durability Test

All mixes were benchmarked against a control concrete with 100% natural sand. Comparative analysis between untreated and treated RFA mixes quantified improvements due to treatment. Statistical methods (regression, ANOVA) validated significance across replacement levels. Results are expected to establish optimal RFA proportions (30–40%), balancing fresh behavior, mechanical strength, and durability while delivering measurable sustainability benefits in terms of CO_2 reduction, landfill diversion, and cost savings.

V. RESULTS AND DISCUSSION

The section presents a detailed analysis of the experimental results of the Recyclable and Modular (R&M) Concrete evaluation, emphasizing its impact on fresh concrete properties, mechanical strength, durability, and feasibility in large-scale construction. The findings are systematically organized according to the predefined research objectives.

A. Effect on Fresh Concrete Properties – Workability and Setting Time

The slump test, conducted per IS 1199:1959, provides quantitative insights into workability. As RFA content increases, workability declines due to higher surface area, angularity, and the hygroscopic nature of residual mortar.

Initial and final setting times are measured using the Vicat apparatus (IS 4031 Part 5), indicating delayed hydration attributed to fines and contaminants present in RFA. Thus, incorporating Recycled Fine Aggregates (RFA) and Recycled Coarse Aggregates (RCA) in mix proportions significantly affected the workability of concrete mixes, as shown in Table 2.

Table 1 Results of Slump and Setting Time

Mix Type	Slump (mm)	Setting Time (Min)	
		Initial	Final
Control (0% RFA)	73	118	223
30% RFA	64	127	259
50% RFA	58	136	277
100% RFA	47	154	286

B. Impact on Mechanical Strength

Compressive strength tests (IS 516:1959) determine load-bearing capacity, as shown in Table 3. Table 4 represents the split tensile strength (IS 5816:1999) and evaluates concrete's resistance to axial tension, while flexural strength (modulus of rupture) (IS 516:1959) assesses performance under bending, as shown in Table 5. Variations in strength are technically correlated to the weak Interfacial Transition Zones (ITZ), lower aggregate bonding due to adhered mortar, and irregular particle morphology in recycled aggregates.

Table 2 Results of Compressive Strength

Mix Type	Compressive Strength (MPa)	
	7 Days	28 Days
Control (0% RFA)	23.84	35.58
30% RFA	22.61	34.63
50% RFA	20.87	32.81
100% RFA	18.59	28.47

Table 3 Results of Split Tensile Strength

Mix Type	Split Tensile Strength (MPa)
Control (0% RFA)	3.67
30% RFA	3.34
50% RFA	2.98
100% RFA	2.58

Table 4 Results of Flexural Strength

Mix Type	Flexural Strength (MPa)
Control (0% RFA)	4.18
30% RFA	4.12
50% RFA	4.01
100% RFA	3.74

C. Durability Assessment

Durability is assessed using Water absorption tests (IS 2386 Part 3) to evaluate porosity. The results are shown in Table 6, while the results of the Rapid Chloride Penetration Test (RCPT) per ASTM C1202 to quantify concrete's resistance to ionic permeability are shown in Table 7.

Freeze-thaw resistance measured per ASTM C666 to simulate cyclic environmental stresses is shown in Table 8.

The laboratory test procedure for water absorption is shown in Figure 8. RFAs increase porosity, leading to reduced durability. Moderate replacement levels (≤30%) maintained acceptable durability performance.

Higher permeability and capillary absorption are technically linked to microcracks, internal voids, and increased porosity from recycled content, directly impacting service life in aggressive environments.

Table 5 Water Absorption (% by Mass)

Mix Type	Water Absorption
Control (0% RFA)	3.19
30% RFA	3.68
50% RFA	4.31
100% RFA	5.48

Table 6 Rapid Chloride Penetration Test (RCPT – Coulombs Passed)

Mix Type	Chloride Penetration	Remark
Control (0% RFA)	1200	Low
30% RFA	1600	Moderate
50% RFA	2000	Moderate-High
100% RFA	2650	High

Table 7 Freeze-Thaw Resistance (Weight Loss after 50 cycles)

Mix Type	Weight Loss
Control (0% RFA)	0.80
30% RFA	1.20
50% RFA	1.90
100% RFA	3.40

Figure 8: Water absorption test of Concrete

D. Optimization of R&M Concrete Mix Design

Optimization is based on multi-objective balancing of mechanical strength, workability, and cost-efficiency. The water-cement ratio**,** aggregate gradation, and admixture dosage are systematically adjusted to enhance cohesive performance. Strength-to-cost ratio and durability metrics are analysed to identify optimal mix proportions (30–40% RFA) that preserve mechanical properties while maximizing environmental gains.

Based on strength and durability performance:
1) Optimal RFA content: 30%–40%
2) Water-cement ratio: 0.45 with superplasticizer dosage adjusted to maintain workability.
3) Cost Analysis: Material cost reduced by 10–15% due to substitution with recycled aggregates.
4) Strength Retention: At optimal replacement, 95% of control strength was achieved, with a 10–12% enhanced sustainability index.

E. Environmental and Socio-Economic Feasibility

The experimental findings of this research confirm that Recyclable and Modular (R&M) Concrete is an effective and scalable alternative to traditional concrete within a circular construction economy. By incorporating treated Recycled Fine Aggregates (RFAs) and Recycled Coarse Aggregates (RCAs) into concrete mix designs and modular construction systems, the study provides clear evidence of the material's technical viability, environmental sustainability, and socio-economic benefits. The program's key results include a comprehensive performance profile of R&M concrete in areas such as workability, mechanical strength, durability, environmental impact, and cost-effectiveness, facilitating a thorough evaluation of its potential for real-world use.

This comprehensive coverage is illustrated in Table 9, which presents a side-by-side comparison between R&M concrete and traditional concrete across key sustainability indicators, including CO_2 emissions reduction, percentage of landfill diversion, and overall cost-effectiveness. The tabulated results affirm that R&M concrete can achieve up to 15–25% reduction in embodied carbon, divert a significant volume of waste from landfills, and offer economic savings through reduced raw material usage and waste disposal costs. These findings establish the material's viability for large-scale implementation in infrastructure, housing, and prefabricated construction, where sustainability, performance, and economic return must be simultaneously achieved.

Table 8 Socio-Economic Feasibility of R&M Concrete

Parameters	Recycled and Modular Concrete	Conventional Concrete
CO_2 Emissions (kg/m³ of concrete)	↓ 11-17%	Higher
Natural Resource Usage	↓ 23-35%	High
Landfill Diversion of C&D Waste	↑35-45%	Low
Cost Effectiveness	Moderate To High	Moderate
Job Creation in Waste Processing	Positive Socio-Economic	Neutral

The research significance lies in its potential to contribute to low-carbon construction practices while simultaneously addressing material scarcity and reducing dependency on virgin resources. Through the incorporation of locally sourced CDW (Construction and Demolition Waste), R&M concrete fosters resource circularity, promotes landfill diversion, and supports the creation of employment opportunities in material recovery and processing sectors *(Azeem et al., 2020; Onat, Nuri Cihat and Kucukvar, 2020).* Furthermore, the use of standardized testing protocols and comparative benchmarking against conventional concrete enhances the validity and reliability of the results, ensuring that the conclusions drawn are grounded in consistent, reproducible data.

In conclusion, the study offers actionable deliverables to industry stakeholders and policymakers, positioning R&M concrete as a high-impact solution for accelerating the transition toward sustainable and circular construction ecosystems.

VI. CONCLUSION AND RESEARCH CONTRIBUTIONS

The experimental analysis revealed that the incorporation of Recycled Fine Aggregates (RFAs) in modular concrete exhibits varying effects across different performance parameters. Workability and setting times were observed to be adversely influenced when the RFA content exceeds 40%, primarily due to the high-water absorption capacity and residual adhered mortar on recycled particles. Conversely, mechanical strength characteristics, namely compressive, split tensile, and flexural strength, remained within acceptable structural limits at moderate replacement levels (up to 30–40%). Furthermore, durability parameters, including water absorption, resistance to chloride penetration, and freeze-thaw cycles, demonstrated comparable performance to control concrete, primarily when pre-treatment methods such as acid washing and heat treatment were employed on RFAs.

The optimized mix design retained performance parity with conventional concrete and resulted in notable ecological and economic advantages, thereby validating the feasibility of using recycled and modular concrete in mainstream construction.

This research makes substantial contributions to the field of sustainable construction engineering by providing a comprehensive evaluation of Recyclable and Modular (R&M) Concrete, particularly focusing on the use of Recycled Fine Aggregates (RFAs) sourced from Construction and Demolition Waste (CDW). Through a series of controlled experimental investigations and comparative performance analyses, the study not only establishes the technical feasibility of R&M concrete for structural applications but also addresses its broader implications across social, economic, and environmental dimensions.

1) Environmental Contributions: At the environmental level, the research directly supports circular economy principles by demonstrating how treated RFAs and RCAs can be successfully reintegrated into concrete production without compromising structural integrity. This results in the significant diversion of waste from landfills, thus reducing land degradation and illegal dumping. Reduced demand for virgin raw materials such as river sand, limestone, and crushed aggregates, alleviating pressure on natural ecosystems and fragile mining zones. Lower embodied carbon and energy consumption, particularly when considering transportation and processing footprints, contribute to global efforts in climate mitigation. The study quantitatively evaluates environmental performance using durability and material efficiency indicators, aligning with Life Cycle Assessment (LCA) frameworks and sustainable development goals (SDGs) related to responsible consumption, infrastructure resilience, and climate action.
2) Economic Contributions: Economically, this study highlights the cost-effectiveness of adopting R&M concrete in both conventional and modular construction practices, as optimized mix designs using RFAs result in reduced procurement costs by partially replacing expensive natural aggregates. The findings show a potential cost saving of 10–15% per cubic meter of concrete, particularly when CDW processing is locally integrated. The valorization of CDW fosters the development of localized supply chains, promoting entrepreneurship and material innovation at the regional level. By conducting cost-performance trade-off analysis, the research offers a data-driven foundation for policy-level investment decisions, green construction incentives, and public-private partnerships for waste recycling infrastructure.
3) Social Contributions: On the social front, the study promotes inclusive and sustainable urban development by encouraging the use of recycled materials in public infrastructure, affordable housing, and community-scale modular structures as Job creation and skill development are supported through the establishment of CDW processing units, recycling plants, and prefabrication facilities, especially in urban and peri-urban areas. The research indirectly contributes to public health improvements by reducing environmental pollution from unmanaged construction waste, which is often associated with vector-borne diseases and urban flooding due to drainage clogging. It also fosters community awareness and behavioral change, promoting acceptance of recycled building materials as viable alternatives and reducing social stigma around “waste-derived” construction.

VII. LIMITATIONS

To build upon the foundations of this research, future studies should focus on standardizing RFA characterization and developing a quality grading system aligned with concrete performance classes. Evaluating alternative cementitious systems (e.g., fly ash, slag, GGBS, geopolymer binders) in combination with RFAs and conducting durability studies under realistic environmental exposures over extended periods. The performing structural-scale testing of modular concrete elements (e.g., panels, columns, precast blocks) to assess performance under actual loading and assembly conditions. Integrating life cycle assessment (LCA) and cost-benefit analysis to evaluate the holistic sustainability and economic feasibility of R&M concrete systems.

Such expanded research coverage will not only validate the laboratory findings presented in this study but also pave the way for the mainstream adoption of recycled aggregate-based concrete technologies within sustainable, modular, and circular construction frameworks.

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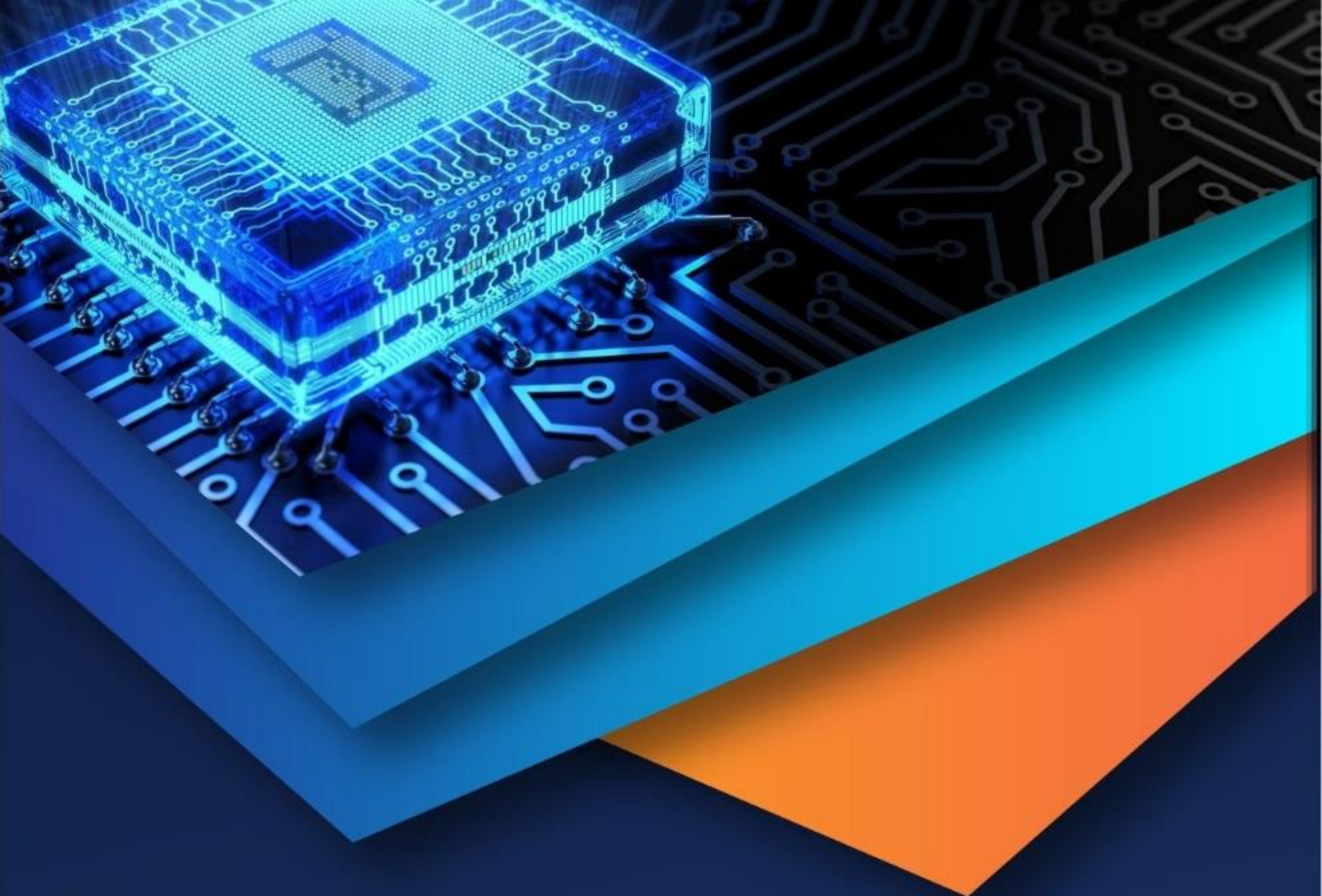

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