



An Experimental Study on Mechanical and Durability Properties of Recycled Aggregate Concrete

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ABSTRACT

The increasing demand for natural aggregates in concrete production has led to the depletion of natural resources and environmental concerns. As a sustainable alternative, recycled aggregates derived from demolished concrete structures have gained significant attention in the construction industry. This study investigates the mechanical and durability properties of recycled aggregate concrete (RAC) by replacing natural coarse aggregates with recycled aggregates at varying replacement levels (0%, 25%, 50%, 75%, and 100%). The primary objective is to assess the feasibility of using recycled aggregates in high-performance concrete while maintaining adequate strength and durability. Experimental investigations were conducted to evaluate the compressive strength, splitting tensile strength, flexural strength, and durability characteristics, including water absorption and chloride penetration resistance. The results indicate that an optimal replacement percentage of recycled aggregates can achieve comparable strength properties to conventional concrete while enhancing sustainability. However, a higher replacement percentage may impact workability and durability due to increased porosity and adhered mortar on recycled aggregates. The study highlights the potential of RAC as an eco-friendly alternative to conventional concrete, contributing to waste reduction and sustainable construction practices. The findings provide valuable insights into optimizing recycled aggregate content to balance performance and environmental benefits.

Keywords: Sustainable concrete; Recycled aggregates; Mechanical properties; Durability studies; Environmental benefits.

1. INTRODUCTION

Concrete is the most widely used construction material worldwide due to its superior compressive strength, durability, and versatility. However, the large-scale consumption of natural aggregates for concrete production has led to the depletion of natural resources and severe environmental consequences, including habitat destruction and increased carbon emissions from mining activities (Mehrzaad and Aly, 2021). The growing demand for sustainable construction materials has prompted researchers and engineers to explore alternative aggregate sources. One of the most promising solutions is the use of recycled aggregates (RA), derived from demolished concrete structures, as a partial or complete replacement for natural aggregates. This approach aligns with global sustainability goals by promoting circular economy principles and minimizing construction and demolition (C&D) waste (Tam *et al.* 2005).

Recycled aggregate concrete (RAC) has the potential to reduce environmental impact, conserve natural resources, and contribute to sustainable infrastructure development (Etxeberria *et al.* 2017). However, challenges such as the quality variation of recycled aggregates, increased water absorption, and

possible reduction in mechanical properties necessitate in-depth research to optimize RAC mixtures and ensure structural reliability (Kou and Poon, 2009).

The construction industry generates significant amounts of waste annually, primarily from demolition activities. Conventionally, this waste is either disposed of in landfills or used as low-grade fill material, leading to land pollution and inefficient resource utilization (Yehia *et al.* 2015). Incorporating recycled aggregates in concrete production presents a viable strategy to mitigate these issues by reducing landfill waste and decreasing the dependency on virgin aggregates.

Recycled aggregates are sourced from processed construction and demolition debris, consisting of crushed concrete, masonry, and other inert materials. While these aggregates retain fundamental properties similar to natural aggregates, the presence of adhered mortar, porosity, and surface roughness can influence the overall performance of RAC. Thus, systematic investigations on RAC properties are crucial to establishing confidence in its use for structural applications (Silva *et al.* 2014).

Recycled aggregate concrete differs from conventional concrete due to the unique characteristics of recycled aggregates, primarily influenced by the

presence of adhered mortar, workability challenges, strength variability, and durability concerns. One of the key factors affecting RAC is the adhered mortar that remains attached to the surface of recycled aggregates after crushing and processing. This adhered mortar is highly porous and less dense than natural aggregates, leading to increased water absorption and reduced mechanical properties. Higher porosity can result in lower strength and durability, making RAC more vulnerable to moisture-related deterioration (Chen *et al.* 2022). The residual mortar also reduces the bulk density of the aggregates, affecting mix design and overall performance. Consequently, effective removal or mitigation of adhered mortar through pre-treatment methods such as washing and mechanical processing is crucial for enhancing the quality of RA.

Another major concern with RAC is its reduced workability compared to conventional concrete. Due to the rough texture and angular shape of recycled aggregates, fresh RAC tends to have lower fluidity and requires additional water or chemical admixtures to achieve the desired workability. Unlike natural aggregates, which are smooth and well-rounded, RA particles increase interparticle friction, reducing slump values and making the concrete less workable. Superplasticizers or viscosity-modifying admixtures are commonly used to improve the flowability of RAC without compromising strength (Xiao *et al.* 2012). Additionally, pre-wetting recycled aggregates before mixing can help control water absorption and maintain better consistency in fresh concrete.

The variability in strength is another challenge associated with RAC. Since the quality of recycled aggregates depends on the parent concrete from which they are derived, RAC can exhibit significant variations in mechanical properties. Concrete structures that undergo demolition often have different mix compositions, exposure conditions, and levels of deterioration, leading to inconsistent aggregate properties. This variability affects the compressive strength and stiffness of RAC, which can impact its structural performance. To improve the quality of RA, proper processing techniques such as sieving, washing, and selective demolition should be implemented. These methods help in removing weak or contaminated particles, ensuring that only high-quality aggregates are incorporated into RAC. Studies have shown that well-processed RA can achieve strength properties comparable to natural aggregates when mix design is optimized (Debieb and Kenai, 2008).

Durability is another critical factor influencing the long-term performance of RAC. Increased permeability and porosity make RAC more susceptible to environmental deterioration, including chloride ingress and freeze-thaw cycles. The higher water absorption of RA leads to greater penetration of aggressive agents,

which can accelerate reinforcement corrosion in reinforced concrete structures (Tavakoli and Soroushian, 2009). In cold climates, RAC is also more prone to freeze-thaw damage due to retained moisture expanding within the pore structure, causing internal cracking and surface scaling. To enhance the durability of RAC, supplementary cementitious materials (SCMs) such as fly ash, silica fume, and ground granulated blast-furnace slag (GGBS) are often incorporated into the mix. These materials help refine the pore structure, reduce permeability, and improve resistance to chemical attacks. Additionally, careful mix proportioning and proper curing methods are essential to mitigate durability issues and extend the service life of RAC (Thomas *et al.* 2013).

While RAC offers a sustainable alternative to natural aggregates by reducing construction waste and promoting resource conservation, its use presents several challenges related to adhered mortar, workability, strength variability, and durability. However, with proper processing techniques, optimized mix designs, and the incorporation of supplementary materials, the limitations of RAC can be effectively mitigated. Further research and advancements in aggregate treatment and mix proportioning will continue to enhance the viability of RAC structural applications (Padmini *et al.* 2009).

Several studies have explored the performance of recycled aggregate concrete, highlighting both its advantages and limitations. **Compressive Strength:** Studies indicate that RAC can achieve comparable compressive strength to conventional concrete when replacement levels are optimized (typically up to 50%). However, higher replacement percentages may lead to strength reductions due to the weaker adhered mortar phase (Tam *et al.* 2005). **Durability Performance:** Researchers have reported mixed results regarding the durability of RAC. Some studies suggest that higher permeability and water absorption can reduce its resistance to aggressive environmental conditions, while others propose that proper treatment methods (such as surface coating or pre-saturation of aggregates) can improve RAC's durability (Silva *et al.* 2014). The use of recycled aggregates significantly reduces carbon footprints associated with aggregate mining, transportation, and landfill disposal. Additionally, RAC can lower construction costs in regions where natural aggregates are scarce or expensive (Tavakoli and Soroushian, 2009).

Recycled aggregate concrete represents a sustainable alternative to conventional concrete, offering significant environmental benefits and promoting resource efficiency in the construction industry. While challenges related to workability, strength variability, and durability need to be addressed, research indicates that with proper mix design and treatment methods, RAC can serve as a viable material for structural and non-structural applications (Xiao *et al.* 2012). This study aims to

contribute to the ongoing efforts to enhance the performance of RAC, paving the way for its broader acceptance in modern construction practices.

2. RESEARCH SIGNIFICANCE

This study aims to assess the feasibility of incorporating recycled coarse aggregates in concrete, focusing on its mechanical and durability properties. The specific objectives include:

- Evaluating the compressive, tensile, and flexural strengths of RAC at different replacement levels (0%, 25%, 50%, 75%, and 100%).
- Analyzing the impact of recycled aggregate replacement on concrete workability and fresh properties.
- Investigating durability characteristics, including water absorption, porosity, and resistance to chloride penetration.
- Comparing the performance of RAC with conventional concrete to determine the optimal replacement ratio for practical applications.
- Highlighting the environmental and economic benefits of using RAC in construction projects.

3. MATERIALS AND METHODS

The materials used in this study include Ordinary Portland Cement (OPC), fine and coarse aggregates (both natural and recycled), water, and chemical admixtures. OPC of 53 grade conforming to IS 12269:2013 was used as the primary binder. The chemical composition and physical properties of cement, including specific gravity, fineness, and setting time, were tested as per IS 4031:1988.

Fine aggregates consisted of river sand, conforming to IS 383:2016, with a fineness modulus of 2.6. Coarse aggregates were partially replaced with recycled coarse aggregates (RA) obtained from demolished concrete structures, following crushing, sieving, and washing. They were classified based on size fractions of 10 mm to 20 mm and tested for water absorption, specific gravity, and impact value. The natural coarse aggregates (NCA) were sourced from a local quarry, while the RA was obtained from a construction demolition waste recycling facility.

The chemical admixture used was a superplasticizer to improve the workability of RAC.

A polycarboxylate ether-based high-range water-reducing admixture was incorporated to counteract the lower workability of RAC, following the dosage recommendations of IS 9103:1999. Water conforming to IS 456:2000 was used for mixing and curing.

Table 1: Mix proportions of RA concrete in kg/m³

Mix Id	Cement	Fine Aggregate	Natural Coarse Aggregate (NCA)	Recycled Coarse Aggregate (RA)	Water	Superplasticizer
M0 (0% RA)	400	650	1200	0	160	3.2
M25 (25% RA)	400	650	900	300	160	3.2
M50 (50% RA)	400	650	600	600	160	3.2
M75 (75% RA)	400	650	300	900	160	3.2
M100 (100% RA)	400	650	0	1200	160	3.2

3.1 Preparation of Recycled Aggregates

Recycled aggregates were sourced from demolished concrete structures and underwent a systematic processing method to enhance quality. The steps included:

Collection and Sorting: Large chunks of demolished concrete were collected and manually sorted to remove unwanted debris such as wood, plastic, and metals.

Crushing: The sorted concrete was crushed using a jaw crusher into coarse aggregate fractions of 10 mm to 20 mm.

Sieving and Grading: The crushed material was sieved to remove finer particles (<4.75 mm) and graded based on size fractions for uniformity.

Washing and Pre-treatment: To reduce the effect of adhered mortar, the recycled aggregates were washed and pre-soaked in water for 24 hours before use. This step helped in lowering the water absorption capacity and improving workability.

3.2 Mix Proportioning

The mix proportions were designed based on the guidelines of IS 10262:2019 for M30 grade concrete (Table 1). Natural coarse aggregates were replaced with

RA at 0%, 25%, 50%, 75%, and 100% levels by weight. The water-to-cement (w/c) ratio was 0.40, and a superplasticizer dosage of 0.8% by cement weight was maintained across all mixes.

3.3 Mixing, Casting, and Curing

The mixing process followed the two-stage mixing approach (TSMA) to improve the bonding of RA with cement paste. The procedure involved:

First Stage: Recycled aggregate was mixed with one-third of the cement and half the water for 1 minute to allow initial coating.

Second Stage: The remaining cement, water, fine aggregates, and superplasticizer were added and mixed for an additional 3 minutes.

Concrete specimens were cast into 150 mm × 150 mm × 150 mm cubes for compressive strength tests, 100 mm × 200 mm cylinders for splitting tensile strength tests, and 100 mm × 100 mm × 500 mm prisms for flexural strength tests, following IS 516:2020 guidelines. The specimens were demolded after 24 hours and subjected to water curing for 28 days at 27°C ± 2°C.

3.4 Testing Procedures

The mechanical properties of concrete were assessed as follows:

Compressive Strength: Tested using a universal testing machine (UTM) of 1000 kN capacity at a loading rate of 140 kg/cm²/min, following IS 516:2020.

Splitting Tensile Strength: Evaluated using cylindrical specimens in accordance with IS 5816:1999.

Flexural Strength: Measured using the three-point bending test, following IS 516:2020.

Water Absorption and Porosity: Determined by drying and weighing concrete samples before and after immersion in water, as per ASTM C642.

4. RESULTS AND DISCUSSION

4.1 Compressive Strength

The compressive strength results of recycled aggregate concrete indicate a clear trend of strength reduction with increasing replacement levels of recycled coarse aggregate. The control mix M0 (0% RA) exhibited the highest compressive strength across all curing ages, reaching 45.8 MPa at 28 days and 48.5 MPa at 56 days. This is expected, as natural coarse aggregates possess superior mechanical properties and lower porosity compared to recycled aggregates. The gradual incorporation of RA led to a systematic decrease in

compressive strength, primarily due to the weaker adhered mortar, higher porosity, and increased water absorption characteristics of recycled aggregates (Rahal, 2007).

At 25% replacement (M25), the compressive strength at 28 days was recorded as 43.0 MPa, which is only 6% lower than the control mix (M0). This indicates that a partial replacement of up to 25% RA can be considered acceptable for structural applications, as the reduction in strength remains within reasonable limits. At 50% RA replacement (M50), the compressive strength dropped further to 40.5 MPa, showing a 12% reduction compared to M0. This suggests that as the proportion of RA increases, the negative effects of weaker interfacial transition zones (ITZ) and increased porosity become more pronounced, leading to strength deterioration. When the replacement level was increased to 75% (M75), the compressive strength at 28 days decreased to 38.2 MPa, marking a 17% reduction compared to the control mix. The decline is attributed to the cumulative effect of adhered mortar, which increases water demand and reduces the overall bonding between the cement paste and aggregates. Additionally, the angular and rough texture of recycled aggregates contributes to lower workability, making it challenging to achieve proper compaction, further impacting the strength development.

At 100% RA replacement (M100), the compressive strength dropped significantly to 35.8 MPa at 28 days, a 22% reduction compared to conventional concrete (M0). This demonstrates that full replacement of natural aggregates with recycled aggregates compromises strength considerably, making it less suitable for high-strength applications without additional modifications. The adhered mortar surrounding recycled aggregates creates weak zones within the concrete matrix, leading to a less dense and less durable concrete structure. Furthermore, the increased permeability of RAC at higher replacement levels makes it more vulnerable to environmental deterioration, such as chloride ingress and freeze-thaw cycles, which could further impact long-term strength retention (Kisku *et al.* 2017).

Despite the reduction in compressive strength with increasing RA content, the strength development trend remains consistent across all mixes, showing significant gains between 7 to 28 days and a slower increase beyond 28 days up to 56 days. This suggests that, although RAC has a lower initial strength compared to conventional concrete, it continues to gain strength over time, particularly when appropriate curing conditions are maintained.

Overall, the results indicate that up to 50% RA replacement can be a feasible option for structural applications, provided that suitable mix design adjustments, such as pre-washing RA, using SCMs like

fly ash or silica fume, and optimizing water-to-cement ratios, are implemented to mitigate strength reduction. For applications requiring higher durability and strength, it is recommended to limit RA replacement to 25% or lower. However, for non-structural or secondary applications, higher RA replacement levels can still be utilized effectively, promoting sustainability by reducing construction and demolition waste. Fig. 1 presents the compressive strength of recycled aggregate concrete.

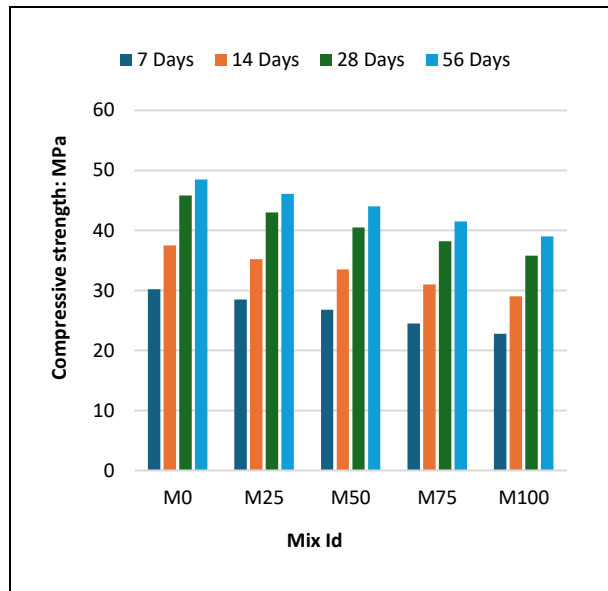


Fig. 1: Compressive strength of recycled aggregate concrete

4.2 Splitting Tensile Strength

The results of split tensile strength and flexural strength tests for RAC indicate a reduction in both properties as the percentage of recycled coarse aggregate increases. This trend aligns with the compressive strength results and highlights the impact of weaker adhered mortar, higher porosity, and lower density of recycled aggregates on the overall mechanical behavior of concrete. While M0 (0% RA) exhibited the highest strength values, the gradual replacement of NCA with RA resulted in strength reductions across all curing ages. However, up to 50% RA replacement (M50), the tensile and flexural strengths remain within acceptable limits, suggesting potential structural applications with appropriate modifications.

The split tensile strength test results (Fig. 2) reveal that M0 (0% RA) achieved 4.2 MPa at 28 days, while M100 (100% RA) recorded the lowest value of 3.3 MPa, reflecting a 21% decrease. The M25 (25% RA) and M50 (50% RA) mixes retained tensile strength values close to the control mix, indicating that partial RA replacement does not significantly compromise tensile performance. At higher RA replacement levels (75% and 100%), the reduction becomes more pronounced due to the lower bond strength at ITZ and the increased presence

of adhered mortar. The higher porosity and increased micro-cracking tendency in RAC reduce its ability to resist indirect tensile stresses, leading to lower split tensile strength. Despite this, the strength development trend remains consistent, showing a significant gain between 7 and 28 days, with a slower increase up to 56 days. This suggests that while RAC exhibits lower initial tensile strength, its long-term development remains similar to conventional concrete with adequate curing.

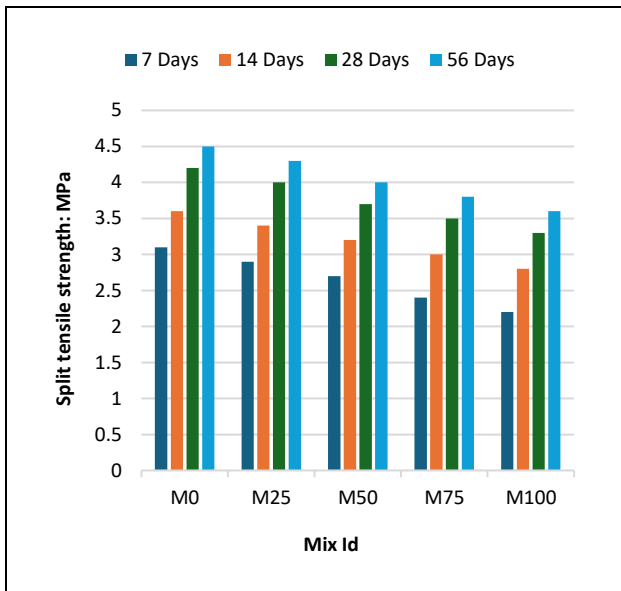


Fig. 2: Split tensile strength of concrete

4.3 Flexural Strength

The flexural strength results (Fig. 3) follow a similar pattern, where M0 (0% RA) exhibited the highest value of 6.5 MPa at 28 days, while M100 (100% RA) recorded the lowest at 5.2 MPa, marking a 20% reduction. The M25 (25% RA) and M50 (50% RA) mixes maintained flexural strength values above 6.0 MPa, making them viable options for structural applications where bending resistance is critical. The reduction in flexural strength is attributed to the weaker bond between cement paste and RA, increased internal voids, and higher stress concentrations at the ITZ. Unlike compressive strength, which is primarily governed by the bulk strength of aggregates and cement paste, flexural strength is more sensitive to microstructural flaws and crack propagation, making RAC more vulnerable to bending stresses. The rough and angular shape of RA particles, while beneficial for mechanical interlocking, also increases stress concentrations, further reducing flexural strength at higher replacement levels.

4.4 Water Absorption

Water absorption is a critical durability parameter in concrete as it directly influences permeability, porosity, and resistance to environmental

deterioration. The results indicate that as the percentage of RA increases, water absorption also increases due to the higher porosity and weaker adhered mortar in RA. The control mix M0 (0% RA) exhibited the lowest water absorption values, recording 1.8% at 28 days and 1.7% at 56 days, which aligns with the dense and low-porosity nature of NCA. In contrast, the M100 (100% RA) mix showed the highest absorption, reaching 3.5% at 28 days and 3.2% at 56 days, demonstrating a nearly twofold increase compared to M0. This significant rise in water absorption for higher RA content is a direct consequence of the porous adhered mortar layer, which retains more water and increases the overall permeability of the concrete (Mugahed *et al.* 2020).

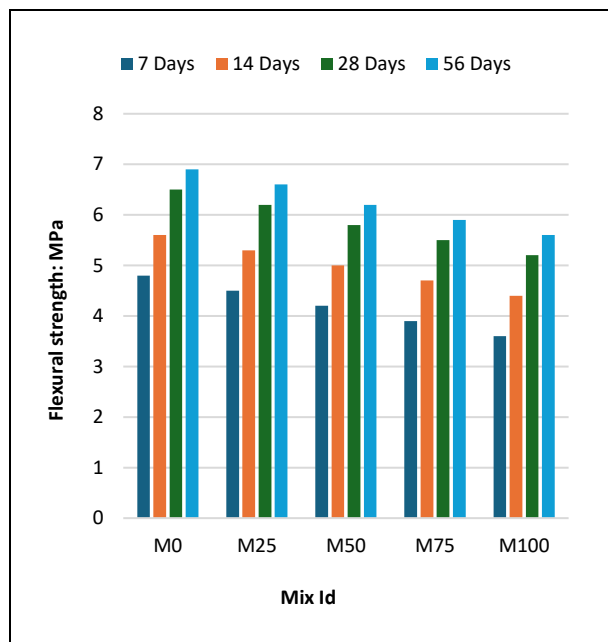


Fig. 3: Flexural strength of concrete

A closer analysis of the data reveals that partial replacements of NCA with RA (up to 50%) maintain reasonable water absorption values. The M25 (25% RA) and M50 (50% RA) mixes exhibited water absorption values of 2.1% and 2.5% at 28 days, respectively, which are only moderately higher than the control mix. This suggests that partial RA replacement does not drastically compromise durability, making these mixes feasible for structural applications. However, at higher replacement levels (M75 and M100), water absorption increased significantly, with M75 recording 3.0% at 28 days and M100 reaching 3.5%. These values indicate that as RA content increases, the overall pore structure of the concrete becomes less dense, allowing for greater water ingress, which may reduce long-term durability and resistance to aggressive environmental conditions.

The time-dependent behavior of water absorption across all mixes shows a gradual decrease between 7 and 56 days, with the most significant reduction occurring between 7 and 28 days. This decline

is attributed to continued hydration of cement particles, densification of the cement matrix, and the filling of voids by hydration products. Even in RAC mixes with high RA content, the progressive reduction in water absorption suggests that proper curing enhances long-term concrete densification, although it does not completely eliminate the effect of increased porosity due to RA (Ryoichi *et al.* 2007).

From a durability standpoint, the increased water absorption in RAC at higher RA levels could lead to greater permeability, making the concrete more susceptible to chloride ingress, sulfate attack, and freeze-thaw deterioration. Therefore, to mitigate these effects, SCMs such as fly ash, silica fume or GGBS can be incorporated to refine the pore structure and reduce permeability. Additionally, pre-washing and pre-soaking RA before mixing can help lower initial water absorption, thereby improving the workability and performance of RAC. Table 2 illustrates the water absorption of recycled coarse aggregate-based concrete.

Table 2. Water absorption percentage of RCA concrete

Mix ID	7 Days	14 Days	28 Days	56 Days
M0 (0% RA)	2.1	2	1.8	1.7
M25 (25% RA)	2.5	2.3	2.1	2
M50 (50% RA)	3	2.8	2.5	2.3
M75 (75% RA)	3.6	3.3	3	2.8
M100 (100% RA)	4.2	3.8	3.5	3.2

5. CONCLUSION

The study confirms that recycled aggregate concrete has the potential to serve as a sustainable alternative to conventional concrete. However, its mechanical strength and durability are significantly influenced by the percentage and quality of recycled coarse aggregates used. Partial replacement up to 50% offers a viable balance between structural integrity and sustainability. Beyond this, marked reductions in compressive, tensile, and flexural strengths are observed. Durability concerns, particularly increased water absorption and porosity, highlight the limitations of high RA content mixes in aggressive environments. Mixes with more than 50% RA are best suited for non-structural applications unless further enhanced. Proper mix design, the inclusion of supplementary cementitious materials, and adequate curing practices can improve performance. Pre-treatment of recycled aggregates and incorporation of fibers or nanomaterials offer promising improvements. While RAC contributes to waste reduction and resource conservation, its successful adoption depends on continued research, technological advancements, and supportive policy frameworks. With appropriate enhancements, RAC can evolve into a reliable and durable solution for sustainable construction.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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