Experimental Study on Post-Earthquake Recycled Concrete Aggregates in Concrete Mixes for Sustainable Structural Application

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Abstract

An earthquake and its impact become a significant challenge for the Himalayan region. Earthquakes result in widespread structural damage, generating enormous construction and demolition waste, particularly concrete debris. Recycled Concrete Aggregates (RCA), obtained by processing demolished concrete structures, offer a viable solution to resource depletion and waste management. This study investigates the fresh and hardened properties of concrete incorporating varying proportions (0%, 25%, 50%, 75% and 100%) of RCA as a replacement for natural coarse aggregates. Standard concrete tests were conducted at different curing periods including slump, compressive strength, split tensile strength, water absorption and density. The results indicate a workability and mechanical performance decline with increasing RCA content due to higher porosity and weaker interfacial transition zones. Nevertheless, mixes with up to 50% RCA showed acceptable strength and durability parameters. The study also highlights the significant influence of RCA on water absorption and modulus of elasticity, emphasizing the need for mix optimization and surface treatment.

Overall, using RCA in concrete is technically feasible and environmentally beneficial, contributing to sustainable construction practices. Fresh Concrete remains superior for primary load-bearing and seismic-resistant structures, with up to 30% better performance under earthquake loading. RCA Concrete, especially with ≤ 50% replacement, can be effectively utilized in non-structural or secondary structural elements, offering a 20-40% environmental benefit through waste reduction and reuse. In post-earthquake reconstruction scenarios, RCA concrete provides a cost-effective, sustainable and locally available alternative, reducing material costs and debris waste by up to 50-60%, providing proper mix design and ensuring quality control.

Keywords: Recycled Concrete Aggregates (RCA), Sustainable construction materials, Construction and demolition waste (C&DW), Waste utilization, Compressive strength, Green concrete.

Introduction

Recently, Turkish monitors observed an earthquake magnitude of 6.4 in Turkey-Syria (2023). Turkey's Disaster and Emergency Management Authority (AFAD) reported that 90 aftershocks followed the quake. The impact of this earthquake is shown in fig. 1. The earthquake has damaged millions of buildings in the past. The consequences have affected the environment with their waste materials, casualties, social and economic disruption in those areas. The increasing demand for natural aggregates and the environmental issues arising from construction and demolition waste have prompted the search for sustainable alternatives in concrete production. The escalating demand for construction materials, particularly concrete, has led to significant environmental concerns including the depletion of natural aggregates and the accumulation of construction and demolition waste[1,2].

In response, recycled concrete aggregates (RCA) have emerged as a sustainable alternative, aiming to mitigate environmental impacts while promoting resource efficiency[3-5]. Recent studies have demonstrated that incorporating RCA into concrete mixes can effectively reduce the reliance on virgin aggregates, thereby conserving natural resources and decreasing landfill usage[6-8]. The inclusion of RCA in concrete is not without challenges. The presence of adhered mortar on recycled aggregates can lead to increased porosity and water absorption, adversely affecting the mechanical strength and durability of the resulting concrete[10,11]. Various methods enhanced the performance of RCA, such as surface treatments and the use of supplementary cementitious materials, to address these issues[13,14].

The rapid pace of urbanization is driving a continuous rise in global concrete demand. As a fundamental construction material, both the production and consumption of concrete have surpassed 30 billion tons annually in recent years[15]. However, concrete production significantly contributes to global warming, with its global warming potential (GWP) estimated at over 600 kg CO_2-equivalent per cubic meter[16]. Additionally, the intensive extraction of aggregates, particularly river sand and high-quality gravel has led to resource depletion and increasing material costs.

Simultaneously, the upkeep and demolition of existing structures generate vast amounts of construction and demolition waste, which consumes land resources and causes environmental degradation[17,18]. To address these challenges, researchers and industry professionals have

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increasingly focused on recycling construction and demolition waste, especially waste concrete, as an alternative source for building materials[19,20,36,41]. Recycled aggregate concrete (RAC), produced using aggregates derived from crushed construction and demolition waste along with other components, has shown significant environmental and economic advantages[8,21]. Numerous studies have examined RAC's mechanical characteristics, durability and service performance at the material level[6,22-25,42-49]. Nonetheless, because standard mix designs often do not account for the properties of recycled aggregates, such as higher porosity, increased water absorption, lower density and higher crushing values, RAC typically underperforms compared to natural aggregate concrete (NAC) in early stages and its properties exhibit greater variability[2,10-12,26-30].

Historically, the lack of sufficient data on the structural behavior of RAC and uncertainties regarding its reliability in load-bearing components led to its use mainly in non-critical applications such as pavements and foundation beds. However, recent robust studies[31-35] demonstrates that by modifying the aggregates and optimizing mix designs, RAC's performance can be substantially improved, potentially matching or surpassing NAC. This progress paves the way for RAC to be used in primary structural components, helping to alleviate aggregate shortages and reduce construction and demolition waste accumulation.

Moreover, RAC's structural safety and its legal, social, environmental and economic implications are gaining attention. This paper study aims to support the broader adoption of RAC in engineering by evaluating its technical and practical viability in structural elements. It also seeks to identify key factors currently limiting its use, thereby advancing the sustainable development of the construction industry. Construction and demolition waste refers to the debris generated during the construction, renovation and demolition of buildings and civil infrastructure. The waste includes many materials such as concrete, bricks, tiles, wood, metals, plastics and other debris. The issue of construction and demolition waste management is a significant problem faced by many countries worldwide. Table 1 shows the existing issues of construction and demolition waste management.

It was observed that managing construction and demolition waste is a complex issue that requires effective regulation, infrastructure and management practices.

Figure 1: A collapsed building in the aftermath of a deadly earthquake in Antakya, Hatay province, Turkey, February 21, 2023

Table 1
Issues about demolition of buildings due to earthquake and management practices

Issues	Practices
Inefficiency in practices	Most C&D waste is disposed of in landfills, which is an inefficient management practice since it accumulates waste in landfills, which can pose environmental problems. Landfills can emit methane gas, a potent greenhouse gas that can contribute to climate change.
Lack of effective regulation	Many countries lack effective regulations for managing C&D waste. This lack of regulation leads to illegal waste dumping, harming the environment and public health.
Limited infrastructure	The lack of proper infrastructure to manage C&D waste challenges efficient waste management. Many countries lack the necessary facilities and equipment to properly transport, separate, recycle and dispose of C&D waste.
Limited recycling	The recycling rate of C&D waste is relatively low compared to other waste streams, such as municipal solid waste. This low recycling rate is due to the difficulty separating and processing the diverse materials in C&D waste.
High cost of management	The cost of managing C&D waste can be high due to the complex nature of the waste stream and the need for specialized equipment and facilities. This can limit the number of companies willing to invest in C&D waste management.

To address the problem, Governments and stakeholders should work together to develop policies and strategies that encourage the recycling and reuse of C&D waste, reduce waste generation and promote efficient waste management practices. Doing so, we can minimize the environmental impact of construction and demolition waste and create a more sustainable future.

Innovative approaches, like accelerated carbonation, have shown promise in improving the quality of RCA. Carbonated recycled aggregate concrete exhibited enhanced compressive and tensile strengths and improved durability against acid and sulfate attacks[35]. Despite these advancements, there remains a need for comprehensive experimental studies to evaluate the performance of concrete incorporating varying proportions of RCA, particularly under different environmental conditions and exposure scenarios[9,12-14,46-53]. This study aims to fill this gap by systematically investigating the mechanical and durability properties of concrete mixes with different RCA replacement levels. In this study, the durability aspects are evaluated in terms of the mechanical properties (compressive strength and tensile strength) of concrete mixes containing varying percentages of RCA[6,7,22,26]. It was ensured that the durability aspects, including water absorption, would help to resist the environmental degradation of RCA-incorporated concrete[10,13,27]. Further, the optimal RCA replacement level that balances sustainability with structural performance is assessed[18,21,31,49-53.]

Review of Literature

The growing interest in sustainable construction materials (SCM) has propelled extensive research on using RCA in concrete production. RCA, obtained by crushing demolished concrete elements, often contains residual mortar adhered to the aggregate surface. This can result in higher water absorption, reduced density and inferior mechanical performance compared to natural aggregates[5]. Managing this debris and ensuring rapid, sustainable reconstruction is a critical challenge in post-disaster scenarios. Recycled Concrete Aggregates (RCA), derived from earthquake rubble, offer a viable solution to debris management and material shortages. For the study of recycled material, the factors considered for the demolished materials such as mechanical properties, water absorption, durability, workability and Fresh properties, seismic performance etc. and detailed literature have been reviewed as follows:

Numerous studies have reported that the compressive strength of concrete decreases as the percentage of RCA increases. This trend is primarily attributed to the weaker interface between the old adhered mortar and the new cement paste[6]. Replacing up to 50% of natural coarse aggregates with RCA resulted in a 10–15% reduction in compressive strength[7]. However, the concrete still met the minimum structural requirements for general use. The mechanical performance of RCA concrete was enhanced by incorporating superplasticizers[8]. The treated mixes demonstrated improved compressive and tensile strengths and a more cohesive matrix. This suggests that chemical admixtures can mitigate some of the drawbacks associated with RCA.

Accelerated carbonation improved the compressive strength and resistance to acid and sulfate attacks[35]. Additionally, using SCMs, such as fly ash (FA) and silica fume (SF), have been proposed to compensate for RCA's drawbacks. According to Limbachiya et al[26], these additives refine the microstructure and improve the durability index of RCA concrete. RCA typically reduces the workability of concrete due to its angular shape and high-water absorption. Rao et al[35] reported lower slump values for RCA mixes unless water-reducing admixtures were used[11]. This can be mitigated by pre-soaking RCA or adjusting the mix design to maintain workability without increasing the water-cement ratio.

The suitability of RCA concrete for structural applications has been debated. While high replacement ratios (above 50%) are typically limited to non-structural uses, moderate levels of RCA (up to 30–50%) have shown promising results for beams, slabs and pavements under moderate loading conditions[12]. Combining RCA with sugarcane bagasse ash also demonstrated good flexural strength, expanding the potential for eco-friendly structural concrete[8]. Recycled aggregates from demolished concrete structures, particularly from earthquake-affected areas, exhibit higher water absorption and porosity than natural aggregates due to adhered old mortar[13]. Despite this, when properly processed and graded, they can achieve sufficient quality for use in structural concrete.

Tam et al[42] investigated the influence of different treatment methods (mechanical and chemical) on improving the quality of recycled aggregates. Their study highlighted that aggressive cleaning can improve RCAs' physical and mechanical properties, making them comparable to natural aggregates. A comparative experimental study using concrete was made from recycled aggregates collected after the 2001 Bhuj earthquake in India[15]. The compressive strength of concrete using 50% and 100% RCA replacement was 10–20% lower than conventional concrete, but still within acceptable structural limits for certain applications.

The structural behavior of reinforced concrete beams incorporating RCAs from earthquake debris was evaluated[16]. While initial cracking and deflection were slightly more pronounced, the overall flexural capacity remained adequate, supporting their use in secondary structural elements. Durability concerns, particularly related to water absorption and freeze-thaw resistance, are often raised when using RCA. The higher porosity of recycled aggregates increases the overall permeability of concrete, making it more susceptible to environmental degradation.

The long-term durability performance of concrete incorporating RCAs from earthquake rubble was explained. Their study included chloride penetration, carbonation depth and freeze-thaw resistance. Results showed that recycled concrete had slightly inferior durability performance. However, applying proper mix design adjustments (like using supplementary cementitious materials such as fly ash or silica fume) mitigated most deficiencies. Durability tests were conducted on concrete mixes with 30%, 50% and 100% RCA from Nepal earthquake debris[18]. Partial replacement up to 50% is optimal without significant compromise in durability and that recycled concrete can be effectively used in non-critical elements and low-rise structures.

The cyclic loading behavior of concrete columns constructed using RCAs from earthquake rubble was tested. Although energy dissipation and ductility were reduced by approximately 15%, the overall load-bearing performance under seismic conditions was within acceptable standards for moderate seismic zones. Kisku et al[22] performed an experimental and analytical evaluation of the structural integrity of RCA-based concrete structures subjected to simulated earthquake loads. Their analysis revealed that proper confinement and mix design compensation (using fibers or nano-additives) can enhance the seismic resilience of RCA concrete.

Silva et al[39] conducted a life cycle assessment (LCA) on recycled aggregates from post-earthquake demolition. They showed that the environmental impact of using RCA was significantly lower due to reduced landfill use and natural aggregate mining. The use of local debris also cuts transportation-related emissions. Xiao et al[49] studied the catastrophic consequences of earthquakes. Structural safety is the subject that requires the most consideration when the RAC application is taken into account. The seismic performance of RAC structures has recently been thoroughly examined through experimentation and simulation research. Data on seismic performances of RAC frames, shear walls and frame-shear walls are collected and analyzed to clarify the characteristics of seismic performances for RAC structures and demonstrate whether RAC structures are practical in earthquake-prone areas.

From the literature, it was observed that (a) there is a lack of standardized treatment methods to enhance RCA properties before use. (b) limited long-term durability data, particularly under aggressive environmental conditions. (c) insufficient regional studies considering locally available RCA sources and waste management systems. These gaps must be assessed and can be utilised for sustainable methods.

Experimental studies have validated the feasibility of using earthquake-demolished recycled concrete aggregates in new concrete. While specific properties like compressive strength and durability may slightly decline with increasing RCA content, proper mix design techniques, additive use and surface treatment can overcome these limitations. The adoption of such practices not only promotes sustainability but also supports faster post-disaster reconstruction and resource conservation. Future studies are encouraged to explore nano-modification, fiber reinforcement and long-term seismic resilience of RCA-based concrete.

Material and Methods

The methodology involves collecting RCA from earthquake-damaged structures and crushing, cleaning and sieving to standard sizes. Concrete mixes were prepared with varying RCA replacement levels (0%, 25%, 50%, 75% and 100%) for coarse aggregates. Standard tests evaluated fresh properties (slump, compaction factor) and hardened properties (compressive, tensile and flexural strength) at 7, 14 and 28 days.

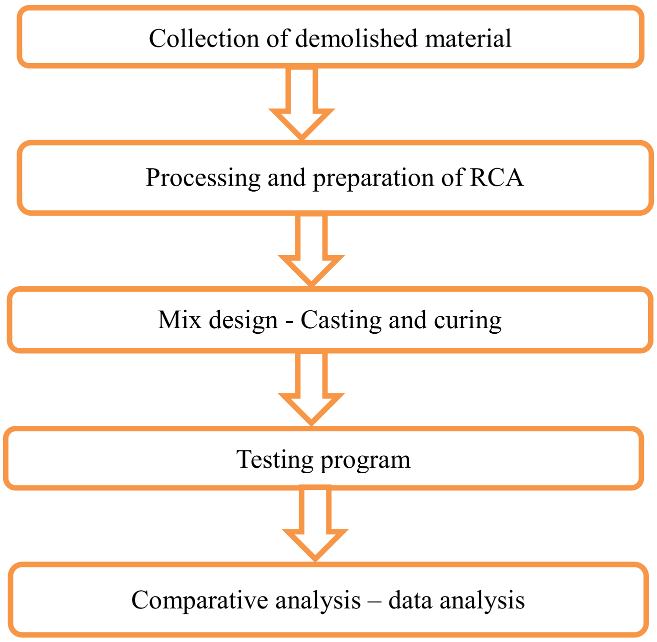

Figure 2: Methodology for RCA

Durability tests, such as water absorption and sulfate resistance, were performed. Specimens were cast and cured in water and results were compared with conventional concrete to assess RCA's structural feasibility and sustainability in construction. The methodology adopted for current study is presented in fig. 2. The detailed steps used in the study are presented in table 2.

Mix Proportions: All mixes were designed for a target compressive strength of 30 MPa at 28 days, with a constant water-to-cement (w/c) ratio of 0.45. The RCA replaced natural aggregates by weight, not by volume. The quantities of the experimental mix and corresponding materials are presented in table 3.

Table 2
Step involved in RCA

S.N.	Step	Details	Significance
1	Material Collection	RCA collected from earthquake-damaged concrete structures	Natural aggregates OPC (43/53 grade) river sand Potable water used
2	Processing of RCA	Crushed using a jaw crusher, cleaned and sieved to 20 mm and 10 mm sizes	Physical properties tested as per IS 2386.
3	Mix Design	M25/M30 grade concrete with RCA	Replacing coarse aggregates at 0%, 25%, 50%, 75% and 100%; designed as per IS 10262.
4	Casting of Specimens	Standard cubes (150mm), cylinders (150×300mm) and beams (100×100×500mm)	Cast for each mix ratio.
5	Curing	All specimens were cured in clean water	For 7, 14 and 28 days.
6	Fresh Property Tests	Slump test and compaction factor test	To determine workability.
7	Hardened Property Tests	Compressive strength, split tensile strength, flexural strength and (optionally) modulus of elasticity were tested	As per IS codes.
8	Durability Tests	Water absorption, acid resistance, sulfate resistance and sorptivity tests were conducted.	For exposure check
9	Non-Destructive Tests (NDT)	UPV and rebound hammer tests were conducted to assess internal quality,	Especially for RCA from earthquake-damaged concrete.
10	Data Analysis	Results analyzed	Compared with conventional concrete
11	Sustainability Assessment	Environmental benefits	Evaluated regarding resource conservation, waste reduction and life cycle impact of using RCA in structural concrete.

Table 3
The experimental mix and corresponding materials quantity

Mix ID	RCA Replacement (%)	Cement (kg/m³)	Water (kg/m³)	Fine Aggregate (kg/m³)	Coarse Aggregate (kg/m³)	RCA (kg/m³)	SP Dosage (%)
M0	0%	400	180	650	1200	0	0.5
M25	25%	400	180	650	900	300	0.5
M50	50%	400	180	650	600	600	0.6
M75	75%	400	180	650	300	900	0.6
M100	100%	400	180	650	0	1200	0.7

Note: Coarse aggregate quantity = NCA + RCA = constant (1200 kg/m³)

(a) Demolished material obtained after earthquake

(b) Preparation and crushing

(c) Testing of sample

Figure 3: Preparation and testing of RCA

Table 4
Physical properties of NCA and RCA used in this study

Property	NCA Value	RCA Value
Specific Gravity	2.68	2.45
Water Absorption (%)	0.8	4.5
Bulk Density (kg/m³)	1550	1300

Preparation of RCA: The material was collected from the demolished site of earthquake-damaged buildings and tested in the laboratory, as shown in fig. 3. The recycled aggregates were obtained by crushing lab-tested M25 concrete cubes and beams. Aggregates were washed, air-dried and sieved to eliminate fines and adhered mortar particles smaller than 4.75 mm. Physical properties of RCA, such as specific gravity and water absorption, were recorded and depicted in table 4. Concrete was mixed in a pan mixer and cast into standard moulds per the IS code. In this study, three different moulds have been used to cast the concrete mix;

a) Cube of size 150x150x150 mm for compressive strength,
b) Cylinders (size 150 x 300 mm) for split tensile strength and c) Prisms (size 100 x 100 x 500 mm) for flexural strength (optional).

Specimens were demoulded after 24 hours and cured in water at 27±2°C until the day of testing (7, 14, 28 days). Each test was conducted on a minimum of three specimens per mix and the average value was considered for analysis.

Results and Discussion

RCA effect on concrete properties: The effect of RCA replacement on concrete properties is shown in fig. 4. The replacement with RCA shows good results with various characteristics of concrete. The compressive strength found decreases gradually with increasing RCA content. Split tensile strength follows a similar decreasing trend. Slump for workability also reduces as RCA content increases, due to higher water absorption by RCA. Fig. 4 (Slump vs. RCA %) shows that the slump value decreased consistently with increasing RCA content. The reference mix (M_0) showed the highest slump of 85 mm, while the 100% RCA mix (M_{100}) recorded the lowest at 50 mm. As shown in figure 2, split tensile strength also declined gradually from 3.1 MPa (M0) to 2.3 MPa (M100). This trend mirrors compressive strength behavior and highlights that RCA inclusion leads to reduced cohesion and increased voids within the concrete matrix.

However, the tensile capacity remained acceptable for general concrete applications up to 50% RCA. This reduction is attributed to higher water absorption capacity of

RCA due to its porous and rough surface texture. Irregular shape of RCA is leading to poor flow and cohesion. Despite the use of superplasticizers, higher RCA content still demanded additional water or admixture dosage to maintain workable consistency.

Water absorption with RCA: Water absorption increased notably with RCA content, as shown in fig. 5. Higher absorption is caused by the old adhered mortar in RCA and micro-cracks and surface pores present in recycled material. This rise in water absorption may negatively impact the durability and long-term service life, particularly in aggressive environments (e.g. sulfate or chloride exposure). Thus, RCA concrete requires additional treatment measures like surface densifiers or pozzolanic admixtures (fly ash, silica fume) to counter this effect.

Compressive strength with RCA: It can be observed that the strength declined with increasing RCA content. M50 (50% RCA) still achieved over 28 MPa, indicating that it remains suitable for structural use in moderate applications. The reduction can be traced to the weaker interfacial transition zone caused by old mortar attached to RCA. Strength development over time followed typical hydration trends (Fig. 6), confirming that RCA does not hinder long-term strength gain, although it begins at a lower base. At 28 days, compressive strength values for mixes M0 to M100 ranged as shown in fig. 6.

RCA with fresh concrete (FC) under seismic condition: Further study is extended to compare the results with seismic forces considered. Table 5 shows the change in various properties of RCA with FC. Five concrete mixes with varying RCA replacement levels (0% to 100%) were evaluated for workability, compressive strength, split tensile strength, water absorption and density.

Conclusion

Based on the experimental investigation into the effects of recycled concrete aggregates (RCA) on the properties of concrete, the following conclusions are drawn:

- Workability decreases with RCA content as the slump value reduced significantly as the RCA percentage increased, mainly due to RCA's higher water absorption and rough surface texture.
- Reduction in compressive and tensile strengths was found at 28 days and both compressive and split tensile strengths decreased with increasing RCA content.

Figure 4: Effect of RCA replacement on concrete properties

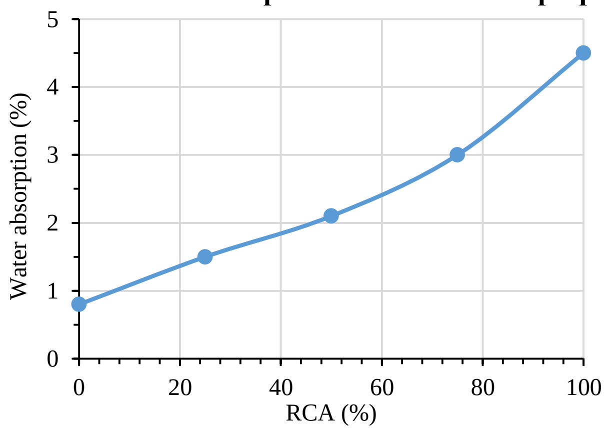

Figure 5: Water absorption Vs RCA replacement

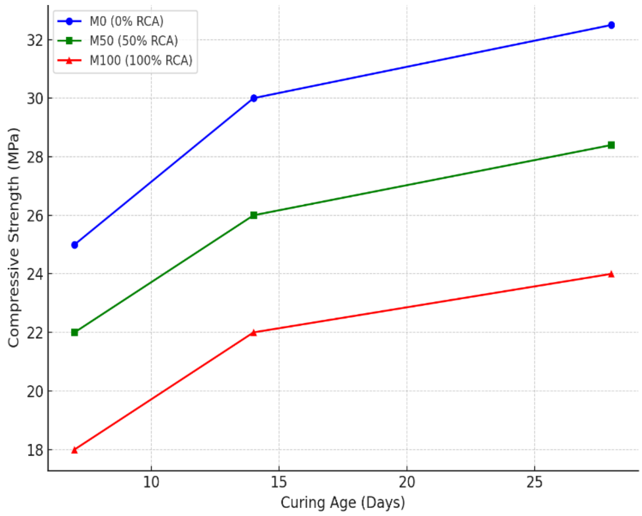

Figure 6: Variation of compressive strength with RCA

Table 5
Percentage (%) change in RCA Vs FC

Property	% Change (RCA vs FC)	Remarks
Compressive Strength	↓ 10–25%	Strength loss increases with RCA% %
Flexural Strength	↓ 15–20%	Weak ITZ and recycled mortar layer
Split Tensile Strength	↓ 10–20%	Reduced cohesion
Load-Carrying Capacity (Beams)	↓ 15–30%	Less suitable for structural elements
Energy Dissipation (Cyclic Load)	↑ 10–20%	Moderate RCA mixes show improved ductility
Crack Width / Spread	↑ 25–35%	Wider cracks under cyclic load
Workability (Slump Retention)	↓ 10–20%	High water demand
Durability (Chloride/Shrinkage)	↓ 15–25%	Use SCMs to improve

- However, up to 50% RCA replacement yielded acceptable strength levels for general structural applications.
- Increased water absorption and reduced durability with RCA mixes exhibited higher water absorption rates which can negatively affect long-term durability, especially in aggressive environments.
- Concrete with 50% RCA replacement offers a viable balance between sustainability, mechanical performance and workability.
- Up to 50% RCA can be used in structural-grade concrete with minor performance trade-offs.
- 100% RCA mixes are more suitable for non-structural applications like pathways, road subbases, or pavement blocks.
- Mix design should account for RCA's higher water demand, either by adjusting w/c ratio or using chemical admixtures.
- The experimental and comparative evaluations of fresh concrete and RCA concrete under simulated earthquake forces reveal critical insights into their respective structural performances.
- Fresh concrete maintains superior mechanical strength, durability and consistency under both static and dynamic loading, RCA concrete presents a viable alternative for specific post-earthquake applications, with both advantages and limitations.
- It was observed that while fresh concrete remains the preferred material for high-performance, seismic-resilient structures**,** RCA concrete can serve as a sustainable and practical solution for rebuilding.

References

1. Ahmad J., Zaid O. and Aslam F., Mechanical and durability performance of self-compacting concrete with RCA and mineral admixtures, *Materials*, **16(2)**, 525 **(2023)**

2. Ajdukiewicz A. and Kliszczewicz A., Influence of recycled aggregates on mechanical properties of HS/HPC, *Cement and Concrete Composites*, **29(9)**, 269–279 **(2007)**

3. Akbarnezhad A., Ong K.C.G., Zhang M.H., Tam C.T. and Foo T.W.J., Effects of the parent concrete properties and crushing procedure on the properties of coarse recycled concrete aggregates, *Journal of Materials in Civil Engineering*, **23(6)**, 403–411 **(2011)**

4. Akhtar A. and Sarmah A.K., Construction and demolition waste generation and properties of recycled aggregate concrete: A global perspective, *Journal of Cleaner Production*, **186**, 262–281, https://doi.org/10.1016/j.jclepro.2018.03.085 **(2018)**

5. Bairagi N., Vidyadhara H. and Ravande K., Mix design procedure for recycled aggregate concrete, *Construction and Building Materials*, **4(4)**, 188–193 **(1990)**

6. Batayneh M., Marie I. and Asi I., Use of selected waste materials in concrete mixes, *Waste Management*, **27(12)**, 1870–1876 **(2007)**

7. Behera M., Bhattacharyya S.K., Minocha A.K., Deoliya R. and Maiti S., Recycled aggregate from C&D waste & its use in concrete – A breakthrough towards sustainability in construction sector: A review, *Construction and Building Materials*, **68**, 501–516, https://doi.org/10.1016/j.conbuildmat.2014.07.003 **(2014)**

8. Braga A.M., Brito J.D. and Veiga R., Incorporation of fine concrete aggregates in mortars, *Construction and Building Materials*, **36**, 960–968 **(2012)**

9. Debieb F. and Kenai S., The use of coarse and fine crushed bricks as aggregate in concrete, *Construction and Building Materials*, **22(5)**, 886–893 **(2008)**

10. De Juan M.S. and Gutiérrez P.A., Study on the influence of attached mortar content on the properties of recycled concrete aggregate, *Construction and Building Materials*, **23(2)**, 872–877, https://doi.org/10.1016/j.conbuildmat.2008.04.012 **(2009)**

11. Etxeberria M., Vázquez E., Marí A. and Barra M., Influence of amount of recycled coarse aggregates and production process on properties of recycled aggregate concrete, *Cement and Concrete Research*, **37(5)**, https://doi.org/10.1016/j.cemconres.2007.02.002, 735–742 **(2007)**

12. Evangelista L. and de Brito J., Mechanical behaviour of concrete made with fine recycled concrete aggregates, *Cement and Concrete Composites*, **29(5)**, 397–401 **(2007)**

13. Gao C., Huang L., Yan L., Jin R. and Chen H., Mechanical properties of recycled aggregate concrete modified by nano-particles, *Construction and Building Materials*, **241**, https://doi.org/10.1016/j.conbuildmat.2020.118030 **(2020)**

14. Gesoğlu M., Güneyisi E. and Özturan T., Properties of self-compacting concrete made with recycled coarse aggregates, *Construction and Building Materials*, **43**, 576–582 **(2013)**

15. Gonzalez-Corominas A. and Etxeberria M., Properties of high-performance concrete made with recycled fine ceramic and coarse mixed aggregates, *Construction and Building Materials*, **68**, 618–626 **(2014)**

16. Grabiec A.M., Klama J., Zawal D. and Krupa D., Modification of recycled concrete aggregate by calcium carbonate biodeposition, *Construction and Building Materials*, **34**, 145–150, https://doi.org/10.1016/j.conbuildmat.2012.02.025 **(2012)**

17. Guo Z., Tu A., Chen C. and Lehman D.E., Mechanical properties, durability and life-cycle assessment of concrete building blocks incorporating recycled concrete aggregates, *Journal of Cleaner Production*, **199**, 136–149, https://doi.org/10.1016/j.jclepro.2018.07.160 **(2018)**

18. Hossain K.M.A. and Poon C.S., Recent developments in concrete with recycled aggregates, *Sustainability*, **12(11)**, 4720 **(2020)**

19. Islam M.S. and Rahman M.M., Sustainable use of waste plastic as a partial replacement for coarse aggregate in concrete, *Construction and Building Materials*, **228**, 116770 **(2019)**

20. Kang T.H.K., Lee Y.H. and Lee S.W., Effect of recycled concrete aggregates on strength and stiffness gain of concrete, *Journal of Building Engineering*, **45**, 103466 **(2022)**

21. Kim J., Properties of recycled aggregate concrete designed with equivalent mortar volume mix design, *Construction and Building Materials*, **301**, 124091, https://doi.org/10.1016/j.conbuildmat.2021.124091 **(2021)**

22. Kisku N., Joshi H., Ansari M., Panda S.K., Nayak S. and Dutta S.C., A critical review and assessment for usage of recycled aggregate as sustainable construction material, *Construction and Building Materials*, **131**, 721–740 **(2017)**

23. Kou S.C., Poon C.S. and Etxeberria M., Influence of recycled aggregates on long term mechanical properties and pore size distribution of concrete, *Cement and Concrete Composites*, **33(2)**, 286–291, https://doi.org/10.1016/j.cemconcomp.2010.10.003 **(2011)**

24. Kwan W.H., Ramli M., Kam K.J. and Sulieman M.Z., Influence of the amount of recycled coarse aggregate in concrete design and durability properties, *Construction and Building Materials*, **26(1)**, 565–573 **(2012)**

25. Le D.H. and Ludwig H.M., Effect of using recycled concrete aggregates on the workability and mechanical properties of concrete, *Journal of Sustainable Cement-Based Materials*, **5(3)**, 155–172 **(2016)**

26. Limbachiya M.C., Leelawat T. and Dhir R.K., Use of recycled concrete aggregate in high-strength concrete, *Materials and Structures*, **33(9)**, 574–580 **(2000)**

27. Liu Q. and Xiao J., Modelling chloride transport in recycled aggregate concrete, *Cement and Concrete Research*, **151**, 106623 **(2022)**

28. Manzi S., Mazzotti C. and Bignozzi M.C., Short and long-term behavior of structural concrete with recycled concrete aggregate, *Cement and Concrete Composites*, **37**, 312–318, https://doi.org/10.1016/j.cemconcomp.2013.01.003 **(2013)**

29. Matias D., de Brito J., Rosa A. and Pedro D., Mechanical properties of concrete produced with recycled coarse aggregates – Influence of the use of superplasticizers, *Construction and Building Materials*, **44**, 101–109 **(2013)**

30. Medina C., Sánchez de Rojas M.I. and Frías M., Reuse of sanitary ceramic wastes as coarse aggregate in eco-efficient concretes, *Cement and Concrete Composites*, **34(1)**, 48–54 **(2015)**

31. Monteiro P., Miller S.A. and Horvath A., Towards sustainable concrete, *Nature Materials*, **16(7)**, 698, https://doi.org/10.1038/nmat4930 **(2017)**

32. Pedro D., de Brito J. and Evangelista L., Influence of the use of recycled concrete aggregates from different sources on structural concrete, *Construction and Building Materials*, **71**, 141–151, https://doi.org/10.1016/j.conbuildmat.2014.08.030 **(2014)**

33. Pedro D., de Brito J. and Evangelista L., Structural concrete with simultaneous incorporation of fine and coarse recycled aggregates: Mechanical, durability and long-term properties, *Construction and Building Materials*, **154**, 294–309 **(2017)**

34. Poon C.S., Shui Z.H. and Lam L., Effect of microstructure of ITZ on compressive strength of concrete prepared with recycled

aggregates, *Construction and Building Materials*, **18(6)**, 461–468 **(2004)**

35. Rao A., Jha K.N. and Misra S., Use of aggregates from recycled construction and demolition waste in concrete, *Resources, Conservation and Recycling*, **50(1)**, 71–81, https://doi.org/10.1016/j.resconrec.2006.05.010 **(2007)**

36. Sahoo S., Tiwari A. and Kumar P., Experimental investigation on strength properties of concrete using recycled concrete aggregate and metakaolin, Materials Today: Proceedings, **33**, 3842–3847 **(2020)**

37. Shi C., Li Y., Zhang J., Li W., Chong L. and Xie Z., Performance enhancement of recycled concrete aggregates – A review, *Journal of Cleaner Production*, **281**, 124962 **(2021)**

38. Shi X., Mukhopadhyay A., Zollinger D. and Grasley Z., Economic input-output life cycle assessment of concrete pavement containing recycled concrete aggregate, *Journal of Cleaner Production*, **225**, 414–425, https://doi.org/10.1016/j.jclepro.2019.03.260 **(2019)**

39. Silva R.V., de Brito J. and Dhir R.K., Performance of cementitious materials with recycled aggregates: A review, *Construction and Building Materials*, **74**, 87–98 **(2015)**

40. Tabsh S.W. and Abdelfatah A.S., Influence of recycled concrete aggregates on strength properties of concrete, *Construction and Building Materials*, **23(2)**, 1163–1167, https://doi.org/10.1016/j.conbuildmat.2008.06.007 **(2009)**

41. Tam V.W.Y., Soomro M. and Evangelista A.C.J., A review of recycled aggregate in concrete applications (2000–2017), *Construction and Building Materials*, **172**, 272–292 **(2018)**

42. Tam V.W., Tam C.M. and Le K.N., Removal of cement mortar remains from recycled aggregate using pre-soaking approaches, *Resources, Conservation and Recycling*, **50(1)**, 82–101, https://doi.org/10.1016/j.resconrec.2006.05.014 **(2007)**

43. Tang Y., Xiao J., Zhang H. and Xia B., Mechanical properties and uniaxial compressive stress-strain behavior of fully recycled aggregate concrete, *Construction and Building Materials*, https://doi.org/10.1016/j.conbuildmat.2022.126546 **(2022)**

44. Tavares A.L., de Brito J. and Sá A., Durability performance of structural concrete containing fine recycled concrete aggregates, *Construction and Building Materials*, **273**, 121692 **(2021)**

45. Thomas C., Setién J., Polanco J.A. and Alaejos P., Mechanical properties of structural concrete containing recycled aggregates from construction and demolition waste, *Waste Management*, **33(5)**, 1095–1103 **(2013)**

46. Verian K.P., Ashraf W. and Cao Y., Properties of recycled concrete aggregate and their influence in new concrete production, *Resources, Conservation and Recycling*, **133**, 30–49 **(2018)**

47. Xia B., Ding T. and Xiao J., Life cycle assessment of concrete structures with reuse and recycling strategies: A novel framework and case study, *Waste Management*, **105**, 268–278, https://doi.org/10.1016/j.wasman.2020.02.012 **(2020)**

48. Xiao J., Recycled aggregate concrete structures, Springer, https://doi.org/10.1007/978-3-319-61989-6, 65–98 **(2018)**

49. Xiao J., Cheng Z., Zhou Z. and Wang C., Structural engineering applications of recycled aggregate concrete: Seismic performance, guidelines, projects and demonstrations, *Case Studies in Construction Materials*, **17**, e01520 **(2022)**

50. Xiao J., Li W., Fan Y. and Huang X., An overview of study on recycled aggregate concrete in China (1996–2011), *Construction and Building Materials*, **31**, 364–383, https://doi.org/10.1016/j.conbuildmat.2011.12.074 **(2012)**

51. Xiao J., Li W. and Tam V.W.Y., An overview of study on recycled aggregate concrete in China, *Construction and Building Materials*, **79**, 68–80 **(2014)**

52. Yuan H. and Shen L., Trend of the research on construction and demolition waste management, *Waste Management*, **31(4)**, 670–679, https://doi.org/10.1016/j.wasman.2010.10.030 **(2011)**

53. Zhang Y., Zhao Y., Wang Y. and Li Y., Recent advances in recycled aggregate concrete: Durability, microstructure and environmental impact, *Journal of Cleaner Production*, **430**, 138970 **(2024)**.

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