Civil and Environmental Engineering
Vol. 0, Issue 0, DOI: 10.2478/cee-2026-0059

Recycling Construction and Demolition Waste into Coarse Aggregates: A State-of-the-Art Review

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Date of Submission: 07 June 2025
Revision Date: 17 November 2025
Date of Acceptance: 17 November 2025

Civil and Environmental Engineering
Journal of the Faculty of Civil Engineering | University of Žilina

Abstract

Natural aggregate depletion and subsequent increase in construction and demolition waste C&D have enhanced the pressure on the construction industry to find solutions using more sustainable materials in concrete manufacturing. Recycled coarse aggregate RCA that has been derived using C&D wastes is an interesting and appealing option that has environmental and economic benefits. The current review takes a critical literature synthesis on the ability to incorporate RCA in concrete, with a specific keenness on mechanical outcomes, durability, structural performance, and environmental responsibilities. The issue of heterogeneity and inconsistency of quality that is often connected to RCA receives its share of attention, as well as the solution to overcoming this drawback. The focus is laid on life cycle assessment LCA research, which considers environmental trade-offs in terms of functional units, emissions cuts, and energy use. The review also considers the recent developments, like surface treatment, optimized mix, and supplementary matters, among others, to improve the performance of RCA. It finds weaknesses in the spheres of standardization, forecasting performance long-term, and sustainability evaluation procedures. All of this, when combined, provides a technically based, integrated approach to what role RCA plays in the sustainable development of civil infrastructure.

Keywords

Recycled coarse aggregate; Construction and demolition waste; Sustainable concrete; Life cycle assessment; Resource efficiency.

1. Introduction

1.1. Background: Overdependence on Natural Aggregates and Growing C&D Waste

The construction industry around the world needs around 40–50 billion tons of aggregates annually, so it is by far the largest consumer of raw materials (Barbuta et al., 2015; Davidovits, 1994; Přikryl, 2021; De Brito and Saikia, 2012; Tam et al., 2018). Natural aggregates like gravel, crushed stone, and sand represent 60–75% of the total concrete volume, and they are usually bought primarily by processes that use much energy, such as quarrying and mining from riverbeds (Naik and Moriconi, 2005; Kashkash, 2024; Fořt et al., 2024; Da and Le Billon, 2022). Dragging out fossil fuels in this manner puts a lot of pressure on the environment, causing issues like land damage, harm to ecosystems, and using non-renewable resources in large amounts (Shamoon et al., 2022; Lu and Wang, 2023).

At the same time, the quick growth of cities and improvements in infrastructure have led to more construction and demolition C&D waste. Many developed and emerging countries see over 30% of their total waste coming from C&D sources (Zheng et al.,2017; Bao and Lu, 2020; Jain et al., 2021). Every year, the European Union produces about 800 million tons of waste from construction and demolition projects (Sáez and Osmani, 2019; Iacoboaea et al., 2019) and countries such as China and India are seeing even bigger jumps because of their rapid urban growth (Jain, 2021; Duan et al., 2019). Dealing with this waste very often leads to illegal dumping, filled and unsafe landfills, and environmental problems in the nearby areas (Siddiqua et al., 2022; Fazzo et al., 2023).

Also, unmanaged construction and demolition waste does not capture any possible recyclable resources. If these materials are used wisely, they can be recycled and brought back into the building for a more circular economy. The use of recycled coarse aggregate RCA in concrete, especially, has proven that it can work in place of natural coarse aggregate (Vahidi, 2024).

Although RCA has many positive aspects, its widespread use in construction is hindered by issues involving different materials, high moisture, and weakening of concrete (Xu et al., 2022). These problems suggest that more research and development are needed to make RCA suitable for sustainable architecture.

1.2. Motivation: Urgency for Sustainable Alternatives in Concrete Technology

The building industry around the world uses many resources and causes harm to the environment, mainly because energy-consuming and polluting materials like Portland cement and natural aggregates are commonly used. The making of one ton of cement results in about 0.9 tons of CO_2, which very much affects the construction industry's emissions of 8% of total greenhouse gas emissions worldwide (Hendriks et al., 1998; Akan et al., 2017). Along with removing and moving natural aggregates, these activities make concrete, which is used everywhere, a material with a high carbon footprint.

With climate change and resource shortages on the rise, more people are adopting sustainable construction practices, especially in line with the United Nations Sustainable Development Goals SDGs (Bexell and Jönsson, 2017). A main goal of this movement is to cut down on using natural resources while using circular economy practices. When construction and demolition C&D waste becomes structural-grade concrete, it helps to reach these goals by cutting down on landfills, conserving new raw materials, and reducing overall emissions (Sabai, 2013; Richardson, 2013).

Recycled coarse aggregate RCA, obtained from pre-processed C&D waste, provides a good substitute for regular coarse aggregate. Tests prove that adding RCA to concrete can help protect land and habitats and reduce pollution from aggregate quarrying, so natural supplies will be protected for generations to come (Kadawo, 2023). Also, improved ways to treat surfaces and design mixtures have raised the performance and durability of RCA concrete, making it more appropriate for common structural uses (Roh et al., 2020).

RCA in concrete is not frequently used in several regions because people have doubts about its quality, there are no consistent standards, and stakeholders are not always informed (Prasittisopin et al, 2025; Sua-iam and Makul, 2024). That is why this article was written: to fill the gaps by bringing together recent studies, showing performance indicators, and promoting the widespread use of RCA in developing sustainable infrastructure (Al-Otaibi, 2024; Mahmoud and Omar, 2024; Han et al., 2023).

1.3. Scope and Objectives of the Review

The major aim of this review is to evaluate how the use of construction and demolition C&D waste as recycled coarse aggregate RCA in concrete fits into sustainable construction. Most reviews look at aspects of recycled aggregates in general, whereas this one is unique in

- Working only with the coarse RCA taken from C&D waste.
- Reviewing trends in several strength and durability indicators, for instance, fracture energy, carbonation, sulfate attack, and long-term shrinkage.
- Using the latest ideas for mixing concrete, for example, using the Equivalent Mortar Volume EMV method and various packing models.
- Figuring out which obstacles might appear, such as rules, how things will be carried out, and how society views the move.
- Advocating for research plans whose foundation is digital tools, hybrid systems, and the concept of a circular economy.

1.4. Novelty of the Study

Unlike prior syntheses that treat recycled aggregates in general, this review is the first to focus exclusively on coarse RCA derived from construction and demolition waste and to integrate four interlinked dimensions: mechanical performance, durability, structural behavior, and life-cycle environmental impacts across studies published through December 2024. It systematically compares 90 research articles and 15 prior reviews, employing diverse functional unit frameworks in LCA, and highlights advanced mixture strategies such as the Equivalent Mortar Volume EMV method and particle packaging models for refining RCA concrete. Crucially, it identifies five key implementation barriers - quality heterogeneity, lack of standards, stakeholder awareness, regulatory gaps, and digital tool integration and proposes a roadmap for future research and practice, grounded in circular-economy principles and digital-enhanced quality control.

This review works to incorporate RCA more widely in the construction and development of structural concrete and infrastructure, following SDGs, SDG 11 Sustainable Cities and SDG 12 Responsible Consumption and Production.

2. Research Method

This study followed a structured research approach inspired by the methodology used by He Bo (Klüppel, 1998). The literature reviewed included peer-reviewed studies from educational journals and academic dissertations. Initially, relevant sources were collected from the Scopus and PQDT databases. To ensure inclusivity, additional Chinese-language sources such as journal articles, theses, and conference papers—were examined through the well-regarded CNKI database. The literature search was conducted using various criteria, including subject area, authorship, and specific keywords.

Because of the challenges in applying LCA to Recycled Aggregate Concrete (RAC), selecting appropriate search keywords was essential for identifying relevant studies. The main terms used included “LCA,” “RAC” (both spelled out and abbreviated), “waste concrete,” and “C&D waste.”

In concrete production, different mixture designs influence the environmental impact of RAC, so this aspect was analysed first. Particular attention was given to the functional unit, a key component in LCA, as variations in its definition can lead to differing conclusions for the same systems. Since recycling involves both waste processing and product creation, it was necessary to ensure the environmental load was appropriately distributed between these stages. To understand how allocation methods influence LCA outcomes, different cost allocation procedures were examined. During the use phase of RAC, carbonation-related CO_2 absorption becomes significant, often resulting in concrete that absorbs more CO_2 than it emits. Additionally, because the composition of natural and recycled aggregates in NAC and RAC differs, the environmental impact of transportation was also evaluated.

2.1. Literature Review Methodology

The study used a three-step method to select the relevant research: (i) deciding on the databases to use, (ii) searching by keywords, and (iii) narrowing down the research studies found. The way the literature review was done is shown in the figure.

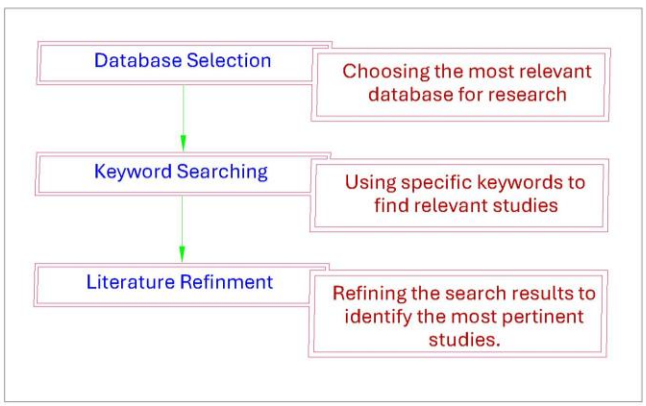

Figure 1: Systematic Research for Literature Review

2.2. Database Selection

Citations and scholarly publications can be searched through several academic databases, such as Scopus, Web of Science, PubMed, and Google Scholar (Falagas et al., 2008) note that Scopus offers certain advantages compared to other indexes, while Wang and Waltman (Wang and Waltman, 2016) explain that Web of Science performs better in journal classification. This study used Scopus and Web of Science as its primary data sources due to these strengths. In addition, Google Scholar was used to ensure that no relevant literature was overlooked.

The phrase “replaced coarse aggregate for effective construction” was searched in the titles, abstracts, and keywords of journal articles and review papers published between 2004 and December 2024. The search was conducted using the Scopus and Web of Science databases. An initial screening yielded 170 relevant publications.

2.3. Sample Searching

After reviewing the abstracts of all 170 retrieved papers and conducting full-text evaluations to determine their relevance to the study's scope, 95 papers were selected. Of these, 90 were research articles and 15 were review papers. Among them, 10 were open access, while the remaining 85 were accessible only through subscription. The years that contributed the most to the selected research were 2023, 2022, 2021, and 2020, with 15, 12, 12, and 10 articles published, respectively. Among the journals, *Waste Management* published the highest number of papers (16), followed by *Resources, Conservation and Recycling* 12, and the *Journal of Cleaner Production* 11. The institutions with the most active research contributions were Hong Kong Polytechnic University, the University of Hong Kong, and Western Sydney University. Notably, Tam V.W.Y. and Yuan H. each authored four papers, followed by Lu W., with three publications (Srour et al., 2013; Yuan, 2017). The selected research materials primarily addressed two main topics: (i) the various roles of aggregates in the waste hierarchy, and (ii) key factors influencing the effectiveness of recycled concrete aggregate (RCA) management. The process followed for conducting the literature review is illustrated in Fig. 2.

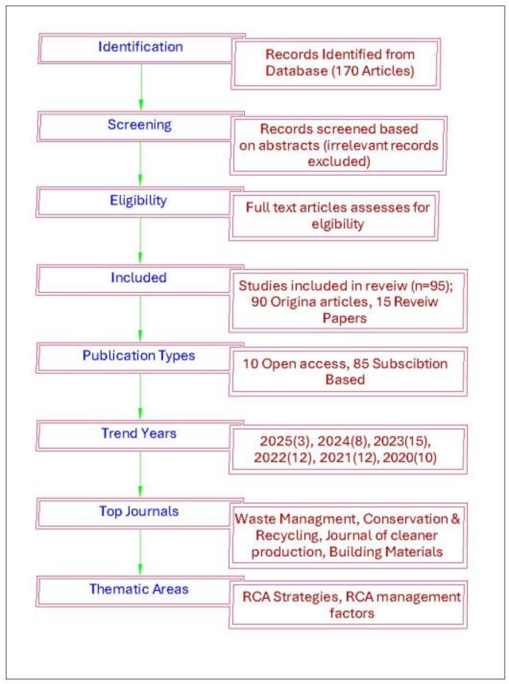

Figure 2: PRISMA Flowchart for Sample Searching

2.4. Discussions

People have differing views on how to manage construction and demolition waste (C&DW), often resulting in conflicting strategies and regulations. For this reason, many efforts around the world have focused on promoting the reduction, reuse, and recycling of C&DW. Effective waste prevention relies on methods tailored to the specific type and source of the waste. To guide these efforts, the waste management hierarchy is commonly applied, as it prioritizes actions based on their environmental benefits. According to this model, waste reduction at the source should be the first priority, followed by strategies for reuse and recycling.

Given that many construction materials—particularly concrete—serve multiple functions, selecting a standardized functional unit for life cycle assessment (LCA) has been challenging. Because different studies have used varying indicators, their findings are not always directly comparable. In LCA studies of concrete, functional units have typically been defined based on performance criteria such as strength, durability, and service life. Panesar and colleagues (Seto et al., 2017) noted that functional units in similar LCAs could be categorized as simple (single variable), moderately complex (two variables), or highly complex (three or more variables).

In assessing the environmental impact of recycled aggregate concrete (RAC), researchers have employed a range of functional units. Some studies (Rodrigues and Joekes, 2011; Zhou, 2020) focused on the volumetric aspects of concrete, while others (Wongkvanklom et al., 2018; Schepper, 2014; Ghoshal and Zeman, 2010) considered both volume and compressive strength. In certain cases, additional factors such as durability, workability, and strength reliability were also considered (Wu et al., 2013; Butera et al., 2015; Ayub, 2021). Table 1 presents the different types of functional units used in studies concerning refrigerants and air conditioning, highlighting the diversity of approaches and the importance of selecting appropriate performance indicators.

Table 1: Overview of Functional Units Commonly Used in Life Cycle Assessment (LCA) Studies of Recycled Aggregate Concrete (RAC), Highlighting Their Defining Parameters, Application Contexts, and Limitations

Designation	Functional Unit	Description
RCU1	Volume-based assessment	Evaluates the environmental impact per cubic meter of RAC compared with an equivalent volume of natural aggregate concrete NAC, considering varying levels of aggregate replacement. (Bandeira et al.; Jin et al., 2024; Epstein, 2018)
RCU2	Volume and strength combined	Uses 1.5 m^3 of concrete as the basis, with mix proportions adjusted to ensure comparable compressive strength between NAC and RAC, often requiring additional cement in RAC mixes. (Oyedele et al., 2013; Serres et al., 2016; Won et al., 2016)
RCU3	Strength-to-impact ratio fcm/GWP	Compares the ratio of mean compressive strength to global warming potential GWP across RAC and NAC mixtures to evaluate efficiency and environmental benefit. (Teh et al., 2017; Khanh and Kim, 2015)
RCU4	Functional performance and durability	Compares RAC and NAC, assuming equal strength, workability, and performance in non-aggressive environments; considers lifecycle equivalence in structural applications. (Lu et al., 2018; Van der Zee and Zeman, 2016)
RCU5	Integrated strength-lifetime index	Evaluates the quantity of concrete required to achieve a defined strength e.g., 1.65 MPa over a specific service life e.g., one year, providing a composite measure for LCA analysis. (Jin et al., 2017; Colangelo et al., 2018; Borghi et al., 2018)

2.5. Effect of Mixture Design Method

Many LCA studies relied on decomposition analysis to determine the environmental impact of concrete production and to identify its primary contributing factors (Ramanathan et al., 2013; Mohseni et al, 2017). The environmental footprint of concrete was influenced by its mix composition, the proportion of its components, and the mix design methodology. Therefore, understanding the influence of mix design on the LCA results of recycled aggregate concrete (RAC) was essential.

Like other RACs, recycled aggregates (RA) consisted of natural aggregates with adhering mortar. This mortar contained unhydrated cement, hydrated compounds, and sand as its main components (Mohan and Mini, 2018). As a result, two Interfacial Transition Zones (ITZs) were formed: one original ITZ between the adhering mortar and the new natural aggregate cement, and a new ITZ between the RA and the cement paste. Due to the presence of these two ITZs and the variability of RAs, RAC often exhibited lower strength, higher shrinkage potential, and reduced stiffness compared to similar concrete made solely with natural aggregates (NAC).

The Equivalent Mortar Volume (EMV) method was developed to address these challenges. This technique adjusted the entire mix—accounting for both fresh and residual mortar—for improved performance. Experiments demonstrated that mixes prepared using the EMV method had greater strength and durability than those designed according to traditional ACI or Bolomey methods (Fang et al., 2024). (Jiménez et al., 2015) confirmed that RACs developed using the EMV approach delivered enhanced performance across several LCA impact categories.

Despite these advances, the application of mix design strategies remained underexplored in LCA assessments of RAC (Wei et al., 2024). Emerging techniques included optimized particle packing, more precise estimation of RA water absorption, and detailed ITZ analysis in diverse material blends. Although these methods offered potential improvements in both performance and sustainability, their integration into LCA studies was limited. Researchers should clearly identify the mix design approach prior to performing LCA and making comparisons. Without this clarity, results may be unreliable—particularly when evaluating mixes created with differing design methods. Moreover, LCA outcomes should inform new mix designs and help guide refinements in mix formulations.

Further developments in RA processing also influenced LCA practices. (Wu et al., 2014) introduced Demolished Concrete Blocks (DCBs) and Demolished Concrete Segments (DCSs) as alternative forms of RA, noting their relatively large size. Unlike traditional RAs, these materials were produced and processed through energy-saving techniques that generated fewer greenhouse gas emissions. The choice of demolition method and equipment significantly affected RAC's environmental impact and long-term performance. Therefore, an LCA model's life cycle inventory (LCI) should account for these variables.

In addition, the functional unit remains central to the LCA framework. A well-defined functional unit ensures consistency, clarity, and applicability across various climatic conditions. As such, this process helps ensure that the assessment remains robust, transparent, and effective for evaluating the sustainability of concrete and related construction practices.

2.6. Advantages and disadvantages of the selected functional units

Life Cycle Assessment (LCA) of recycled aggregate concrete (RAC) has employed several functional units to improve accuracy. The simplest unit, referred to as RCU1, represented the environmental impact of one cubic meter of concrete. Although RCU1 was widely used in early studies due to its simplicity, experts noted that it failed to account for performance, as RAC's compressive strength was often up to 10% lower than that of natural aggregate concrete (NAC) when using the same water–cement ratio.

To address this limitation, RCU2 combined both volume and compressive strength as its functional basis. This allowed adjustments such as increasing cement content by approximately 5% or reducing water content to make RAC comparable to NAC. However, RCU2 typically assumed equal performance conditions and did not sufficiently account for the long-term quality and durability of materials.

RCU3 introduced corrections based on volume, strength, and durability. This approach enabled more accurate comparisons, especially for structures exposed to harsh environmental conditions such as carbonation or chloride attack. While more complex, RCU3 offered a deeper understanding of system performance and environmental impact. Nevertheless, it remained limited in predicting durability losses in extreme exposure scenarios—such as sulfate-rich environments with frequent wet-dry cycles and failed to reflect the environmental burden associated with maintenance activities that often required significant resource input.

RCU4 focused on strength reliability, assessing average strength, variability, and the probability of failure for both RAC and NAC. This approach made it possible to determine the precise amount of RAC needed to achieve performance parity with NAC. However, it required extensive experimental data to be applied effectively.

Selecting an appropriate functional unit is essential in LCA, as it strongly influences the sustainability assessment of RAC. While Type A concretes are produced using fewer raw materials, Type B concretes offer superior long-term performance and reduced environmental impacts over time. For this reason, performance, durability, and maintenance requirements must all be considered when conducting LCA.

3. Characteristics of Recycled Coarse Aggregates (RCA)

3.1. Source and Processing of C&D Waste

C&D waste includes things like concrete, bricks, masonry, wood, glass, metal, and asphalt, which form a mixed waste created in the process of building, renovation, and demolition (Dos reis et al., 2021). It is often seen as a good secondary resource these days, especially used to produce recycled coarse aggregates RCA for green concrete. Most of the usable RCA is created by crushing and processing waste concrete, which makes up around 50%–60% of all C&D waste (Ahmed et al., 2020; Majhi et al., 2018).

The effective operation of RCA depends on the quality of the C&D waste that goes into it. Recycling materials from strong and carefully designed buildings or carefully examined specimens usually gives RCA that is more effective and contains less contamination. How well concrete is formed, what it consists of, how much strength is in it has, and how it was set also impact RCA quality (Ulsen et al., 2019; Djamarani and Clark, 1997).

a) Construction demolition waste b) Sort waste concrete and artificial crush c) Separate large concrete particles

d) Separation of dust particles from aggregates e) Sieve f) Clean and dry

Figure 3: Processing of Recycled Aggregates

C&D waste is turned into RCC using various mechanical procedures such as

1. In primary crushing, the demolished concrete is crushed and made smaller with a jaw or impact crusher (Ivanovskis, 2019).

2. The next step is secondary crushing and screening, where coarse particles ≥ 4.75 mm are reduced and separated (Ouyang et al., 2023).

3. The process uses manual or automatic techniques such as magnetic separation and air classifiers for removing waste particles like steel, wood, plastic, and gypsum (Verma et al., 2023).

4. At times, RCA will follow a process of water cleaning or acid washing to restrict the amount of old mortar stuck to RCA, which reduces the high-water absorption and porosity (de Brito et al., 2013; Kazemian et al., 2019).

Modern factories also use mechanical grinding, different types of heat treatment, and carbonation to refine recycled chips. They are meant to lower excess mortar, enhance how mortar sticks to the surface, and solidify the microstructure.

Following international guidelines, such as those in RILEM TC-121 (Kurda et al., 2018), leads to the same results for particle size, density, and cleanliness. Yet, there are differences from place to place, so performance standards can vary from one set of laws to another. The application of RCA in concrete structures depends on how C&D waste is gathered and handled. The site needs to be organized well, and only a thoroughly cleaned RCA can achieve the high standard.

3.2. Physical and Mechanical Properties of RCA

Recycled coarse aggregate RCA in concrete behaves the way it does because it has distinct physical and mechanical characteristics caused by the mortar, microcracks, and larger porosity it carries. To determine if RCA is right for load-bearing uses and to make the right mixture, one must understand the differences. Compared to virgin aggregates, RCA carries about twice the water absorption and a 20–40 % reduction in stiffness, key parameters to consider when adjusting mix water and serviceability checks (Tam et al., 2007; He et al., 2023; Rahal, 2007).

Recycled coarse aggregate RCA does not have uniform strength since it depends on building strength, curing, crushing method, and where and how the original concrete is demolished. A high amount of mortar left in the bricks decreases density and lets the bricks absorb more. One can handle these problems by doing acid treatment, ensuring proper RCA quality, and adding more cementitious materials (Liang et al., 2022; Alengaram, 2011; Thomas, 2018).

Table 2: Comparison of Physical and Mechanical Properties of Natural Aggregates NA and Recycled Coarse Aggregates RCA

Property	Natural Aggregate NA	Recycled Coarse Aggregate RCA
Bulk Density [kg/m^3]	2600–2700	2100–2400
Water Absorption [%]	0.5–2.0	5.0–8.0
Aggregate Crushing Value ACV, [%]	20–25	25–35
Modulus of Elasticity [GPa]	30–40	18–26
Abrasion Resistance LA Abrasion, [%] loss	20–25	30–40

3.3. Influence of RCA Characteristics on Concrete Behavior

While using recycled coarse aggregates RCA instead of natural coarse aggregates NCA in concrete changes its fresh and hardened properties. This comes about because the RCA surfaces still have mortar stuck to them; they can absorb more water, have lower density, and have natural weaknesses. As a consequence, knowing how RCA affects the behavior of concrete is necessary to produce successful engineering performance-based mixes.

Conventional concrete is typically much easier to handle than RCA concrete, which is less stable. The coarse texture and angled form of RCA, together with its greater water absorption, make it take up more water, which reduces the net free water in the mix. If the RCA is not pre-saturated and the amount of mix water is not adjusted, tests have shown that up to 30–50% of the slump can be lost (Butler, 2011; Ismail and Ramli, 2013; Fernandes, 2021). Because there are more air bubbles in RCA, it may be necessary to add more water or use water-reducing admixtures to get the desired workability level. Compressive strength is lower in concrete with RCA compared to regular concrete. Most reductions in strength are between 5% and 25%, depending upon the amount of recycled concrete and its quality (Pliya, 2019). Loss is more noticeable when the RCA content is higher because there is poor bonding between layers, and the mortar does not stick well. In tensile and flexural strength, patterns are found to be similar. Having microcracks in RCA and a weaker ITZ causes stress to be transferred less efficiently, but using fiber reinforcement or SCMs has been shown to lessen this problem. Because the attached mortar is softer and the aggregate more flexible, RCA concrete sometimes has a modulus of elasticity that is 20–40% lower than that of natural aggregate. Higher drying shrinkage and creep may occur in RCA concrete, and this leads to more carbon dioxide and chloride entering the concrete, which can lead to steel reinforcement corrosion if appropriate action is not taken in the mix. RCA properties and the content they contain can influence their effects, so extra care should be taken when using them for prestressing or in structures. Some research indicates RCA concrete performs as well as standard concrete when heated, thanks to its increased porosity that reduces the chance of the concrete cracking and popping off (Leite and Monteiro, 2016; Panghal and Kumar, 2024). SEM and XRD examinations have found that adding RCA to an Al–Si alloy makes the interfacial transition zone ITZ less homogeneous and fuller of pores (Bansal, 2025; Yang et al., 2023; Nikmehr, 2024). Because there are more microcracks and voids in this zone, it straightaway impacts how strong and durable the material is. Special treatments on the top layer, such as carbonation or nano-silica coating, can improve the ITZ and return concrete performance to what it was before reinforcement.

Table 3: Comparative Behavioural Performance of Natural Aggregate Concrete and RCA Concrete

Property	NA Concrete	RCA Concrete
Slump [mm]	75–100	50–75 without adjustment
Water Absorption [%]	0.5–2.0	5.0–8.0
Compressive Strength [MPa]	35–55	28–50 at 28 days, depending on %RCA
Tensile Strength [MPa]	2.8–4.5	2.0–3.8
Modulus of Elasticity [GPa]	30–40	18–26
Water Permeability [m/s]	$<1\times10^{-11}$	$>3\times10^{-11}$
Drying Shrinkage [με]	400–600	500–800
Chloride Diffusion [10^{-12} m^2/s]	1.0–2.0	2.5–4.5
Creep Strain at 90 days, [με]	1200–1800	1500–2400

3.4. Treatment and Enhancement Techniques for RCA

Since recycled coarse aggregates RCAs cannot match the effectiveness of natural aggregates, people have devised multiple methods to overcome spots with sticking mortar, cracks, and bigger pores. Such treatments boost the strength, density, and durability of RCA, which makes it suitable for use in significant construction projects (Alqarni, 2021; Savva, 2021; Atmajayanti and Haryanto, 2017).

Grinding, shifting, and scrubbing are steps taken during mechanical restoration to remove the extra mortar and weak spots. The process of rotary double crushing and polishing decreases water absorption and makes the mineral heavier. Based on their research, Verma et al. reported that mechanical grinding strengthened cement by up to 15% by making the aggregate better and decreasing interfacial porosity (Forero et al., 2022; Yunusa et al., 2022).

We can make the structure of RCA better by placing it in acetic or citric acid to break down old calcium-rich mortar. Acid treatment was found by Ismail and Ramli to decrease the drying shrinkage and raise the elastic strength of RCA concrete (Al-Bayati et al., 2016). On the other hand, acid soaking needs special care and water conservation, which prevents it from being used on a large scale. Heating RCA to temperatures of 300–600°C creates cracks in the joint, which makes it possible to break up and remove the masonry. Doing this increases the strength of concrete without many open spaces, but it can damage the concrete and create small cracks if not done correctly (Farahani et al., 2025; Li and Wu, 2022). CO_2 curing is expected to benefit mortar, since it reacts CO_2 with calcium hydroxide to create calcium carbonate, leading to denser material, lower water absorption, and higher durability. This way of building helps remove carbon dioxide from the air, fulfilling the goals of eco-friendly construction (Pallapothu, 2024; Tamayo et al., 2019).

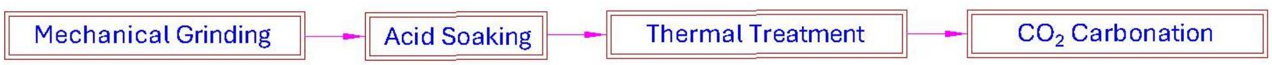

Figure 4: Road Map for Mortar Treatment Process

4. Mechanical Performance of RCA-Based Concrete

4.1. Compressive, Tensile, and Flexural Strength

The load-bearing abilities and safety of concrete depend a lot on its strength. Because of its higher porosity, unsteady composition, and a weaker zone between two aggregates, recycled coarse aggregate RCA impacts concrete's compressive, tensile, and flexural strength differently according to how much is used, how it is processed, and the mix used.

Compressive strength in RCA-based concrete is lessened due to weaker RCA particles and more microcrack paths in the residual mortar. Studies have revealed that when RCA comprises 20% to 50% of the strength aggregate, it only causes a slight decrease 5–10% in strength, especially if the RCA is graded and well-treated. On the other hand, RCA concrete with high replacement ratios over 50% can see a drop in compressive strength of over 15–25%, most often for poor-quality or untreated RCA (Tamayo Castaneda, 2020). Kazemian et al found that the 28-day compressive strengths of RCA concrete were anywhere from 28 to 48 MPa depending on the amount replaced and the treatment used.

Both tensile strength and microstructure matter since they are closely related to how well the aggregates bond with the mortar. RCA concrete is known to have tensile strength 15–25% lower than that of natural aggregate concrete at the same water-to-cement ratio w/c. If supplementary cementitious materials SCMs or fibers are used, some of the strength that is lost may be restored.

The behavior of a material under bending forces , flexural strength often depends on the quality of the ITZ and aggregate interlock. The work done previously demonstrated that concrete with 30% recycled aggregate showed only a 10% decrease in flexural strength. However, higher percentages required a mix of slag or fly ash; otherwise, strength was reduced further (Xiao et al., 2006; Butler, 2013).

Table 4: Comparison of 28-Day Average Strength Properties of Recycled Aggregate Concrete (RAC) at Varying Replacement Levels

Strength Type	Natural Aggregate Concrete	RCA Concrete 20–50% RCA	RCA Concrete ≥50% RCA
Compressive Strength [MPa]	40–60	35–48	28–40
Tensile Strength [MPa]	3.0–4.5	2.5–3.8	2.0–3.2
Flexural Strength [MPa]	4.5–6.0	4.0–5.4	3.5–5.0

4.2. Modulus of Elasticity and Fracture Energy

Serviceability, resistance to cracks, and stiffness depend heavily on structural concrete having the right modulus of elasticity and fracture energy. Working with recycled coarse aggregates RCA results in significant variations in these parameters, mainly because of RCA's traits: more porosity, remaining mortar, and many microcracks.

Because the mortar in RCA concrete is less stiff and there are voids and microcracks inside it, the modulus of elasticity E is lower in RCA compared to conventional concrete. A lot of studies find that the RCA content continues to reduce the elastic modulus by 20–40%. Tests by Ismail and Ramli showed that the modulus of elasticity in RCA concrete declined from about 33 GPa when natural aggregate was used to as little as 19–22 GPa when all aggregate was replaced with RCA (Choubey et al., 2016; Moolaei et al., 2021).

To prevent a drop in E, adding silica fume and fly ash helps increase concrete density, and using improved RCA plus the EMV method produces a better mix. You can increase the fracture energy of RCA concrete by adding nano-silica, curing it in carbonation, or reinforcing its inside with fibers.

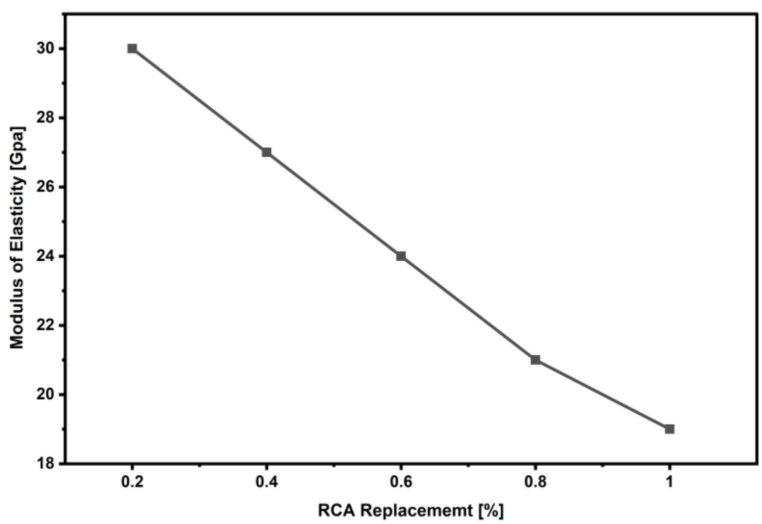

Figure 5: Modulus of Elasticity with RCA Replacement Graph

They are key for modelling structures through finite element analysis and for predicting the range of cracks that develop under normal service loads. Structural design codes must include considerations for reduction in E and Gf if RCA is to be used.

4.3. Load-Bearing Capacity in Structural Elements

The performance of recycled coarse aggregate concrete RCAC under stress determines its suitability for structural applications. Different experiments have measured how flexural, shear, and axial beams, columns, and slabs made with RCA perform against those built with typical concrete (Hossain, 2021; Alibeigibeni et al., 2025).

Beams made with RCA substitution usually have similar flexural strength when suitable mix additions water-cement content, supplementary cementing materials are applied. Tamayo et al. 2019 stated that flexural strength remained between 90 and 95 percent for specimens with RCA values up to 50 percent. No alteration of the basic bending process was noticed, since both the neutral axis depth and failure mode were the same as those of standard concrete.

Because aggregate quality strongly affects the size of RCA concrete microcracks, RCA members become more sensitive to the mix. In their research, Xiao and Zhang, 2005 recorded about a 10–15% fall in beam strength with 100% RCA, but placing stirrups more closely partly improved the strength. The cracks in RCA beams are wider than those in NA beams, but the distribution and direction of crack growth are the same.

Axially loaded columns and short, squat members tend to be less strong than normal when the load is eccentric and placed in the middle of the member. By choosing proper mix designs and adding sufficient reinforcement stirrups, fiber, schools can help limit the performance difference. (Wu and colleagues, 2011) showed that columns with added RCA have load capacities of 85–90% of those made from NA concrete.

RCA concrete can be used for slabs and beams because it does not need prestressing. Little or no design changes are generally made below a 50% return on capital asset RCA. Critical elements should get an additional layer of RCA or mixing with a blend of steel fibers and SCMs.

Table 5 : Structural Performance Comparison: NA vs. RCA Concrete Elements

Structural Element	Metric	NA Concrete	RCA Concrete ≤50%
Beam Flexure (Tamayo et al., 2019)	Ultimate Moment [kNm]	78–85	72–80
Beam Shear (Xiao Jiabin et al., 2006)	Shear Load [kN]	40–50	35–45
Column Axial (Wu Xu et al., 2011)	Ultimate Load [kN]	550–600	470–520
Crack Width (Xiao Jiabin et al., 2006)	At Ultimate Load [mm]	0.6–0.9	0.8–1.2

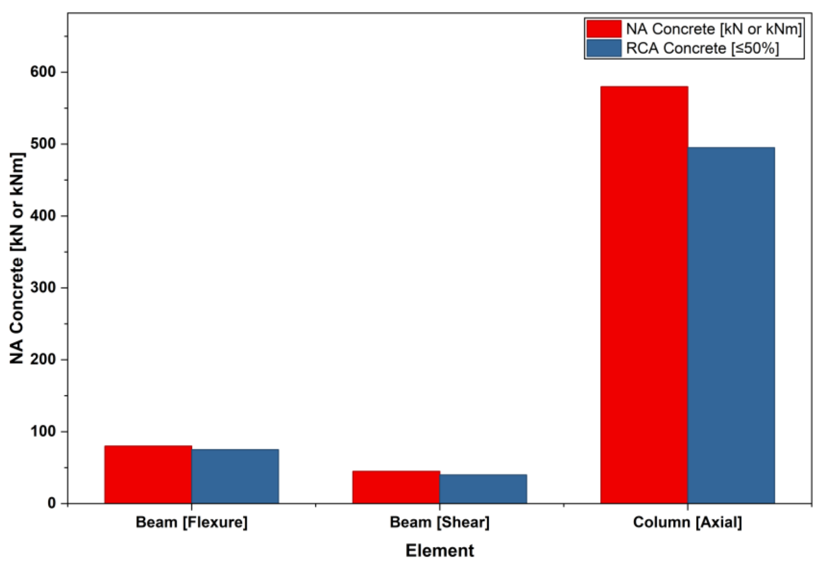

Figure 6: Comparison of Ultimate Load Capacities for NA and RCA Concrete in Structural Elements

4.4. Influence of RCA Replacement Levels

The way recycled aggregate concrete RAC behaves depends greatly on the amount of recycled coarse aggregates RCA used in place of natural coarse aggregates. The studies show that as the percentage of RCA in concrete increases, the main strength properties like compression, tensile, and flexural all progressively decrease. With less than 30% of steel being replaced, strength loss is usually small less than 10% and still acceptable for the structure. A loss of around 6%

compressive strength was found for 30% RCA, but 15–25% drops are typical for concrete with between 50 and 100% recycled content (Peng et al., 2018; Lmmelamn, 2013; Singh, 2021).

RCA decreases modulus of elasticity much more than compressive strength, and at 100% RCA, there can be up to 40% stiffness loss thanks to the weak mortar and many microcracks. This factor has to be considered in serviceability design. When the RCA ratio reaches more than 50%, durability reduces unless some SCMs or fibers are used. Using EMV and curing technology increases the performance of rubber at raised RCA values.

Table 6 : Structural Application Guidelines for Recycled Concrete Aggregate (RCA) in Reinforced Concrete - Recommended Use Based on Replacement Levels, Mechanical Performance, and Durability Considerations

RCA Replacement Level	Mechanical Performance	Durability	Recommended Application
0–30%	Minor reductions <10%	Comparable to NA concrete	All reinforced concrete general use
30–50%	Moderate loss 10–20%	Acceptable with SCMs	Beams, slabs, secondary structural elements
50–100%	Significant strength reduction	High permeability risk	Pavements, foundations, non-structural use

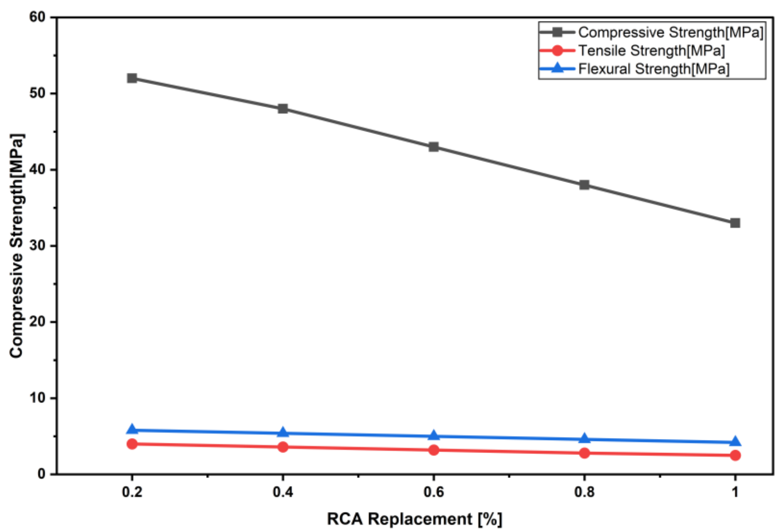

Figure 7: Strength Reduction Trend with Increasing RCA Replacement Percentage

5. Durability and Long-Term Performance

5.1. Water Absorption and Permeability

To assess long-term concrete durability in harsh situations, water absorption and the ability to absorb water are very important. Concrete that includes recycled coarse aggregate RCA is not like natural aggregate concrete NAC because the RCA has porous adhered mortar, and this increases both void space and the interfacial transition zone. Several studies have proven that the water absorption of RCA concrete is generally 30–70% higher than that of NAC using similar raw materials. Tests show that, before any treatment, the absorption of RCA was around 5.0–6.2%; meanwhile, the control NAC mixes had values around 2.3–2.8%. RCA can have its water absorption reduced to less than 4% by methods such as grinding or acid treatment, and this improves its ability to resist water damage. Adding silica fume or slag to the mix helps to improve the pore structure and decrease the ability of water to be absorbed. This reduction in permeability reduces the chance of aggressive elements entering the concrete. (Cui et al., 2015; Lin and Wu et al., 2022; Al-Ghalibi and Mohamad,

2021) RCA concrete has higher initial permeability, especially when the replacement levels are higher than 50%. Yet, the increase in permeability tends to be more complex than predicted by a simple increase, and it can be managed with proper mix design methods such as

1. Lowering the water-to-binder mix ratio.
2. Use of pozzolans in the mixture.
3. Water-reducing admixtures can be used in the mixture.

It has been reported by (Dimitriou et al., 2018) that the permeability of raw RCA concrete is about 8.5 times less than that of NAC permeability. 35% less permeability was seen in pretreated CO_2 cured or acetic acid-soaked RCA mixes compared to the untreated counterparts.

Table 7 : Design Considerations for Recycled Concrete Aggregate (RCA) Mixes

Concrete Type	Water Absorption [%]	Permeability [m/s]	Durability Class
Natural Aggregate NAC	2.3–2.8	8.5×10^{-12}	High
RCA Untreated	5.0–6.2	$1.5–2.2 \times 10^{-11}$	Low to Medium
RCA Treated + SCM	3.2–4.1	$9.5–1.2 \times 10^{-11}$	Medium to High

Durability loss is reduced when the following is done:

1. You should not replace more than 40% of RCA in exposure classes XS1–XS3 chloride environments.
2. You can add RCA to a mix of fly ash 15–30% or silica fume 5–10%.
3. You may increase the curing time or use carbonation to improve how the concrete is packed.

5.2. Chloride Penetration and Carbonation

Durability problems in concrete may be caused by nitrogen dioxide, carbon dioxide, or chloride ions because they can corrode the inside structures and weaken the concrete surface. The weakening of recycled aggregate concrete RAC is more harmful than that of traditional concrete for the reason that more residual mortar in the recycled aggregates leaves it porous and non-uniform with soft internal structures. In particular, chloride ions are able to enter RAC faster as the mortar is more connected and has extra absorption pores. Zheng et al., 2017 found that RAC has higher chloride diffusion coefficients from 1.7×10^{-12} to 2.9×10^{-12} m^2/s than natural aggregate concrete, which had a coefficient of 1.0×10^{-12} m^2/s under similar curing conditions. You can also use RCA pre-conditioning and include SCMs to help stop chloride from permeating concrete materials. When acetic acid and silica fume were added diffusion was decreased by 28%. It was also revealed (Possan et al., 2017) that exposure to 4% CO_2 for 28 days increased the carbonation depth of RAC by 65%.

Even so, we can look at this drawback from two angles. Controlled conditions make use of carbonation curing to act as a helpful step before mixing, since it can lessen the permeability and increase preliminary strength by growing calcium carbonate inside the RCA pores.

Table 8: Durability Parameters of NA Concrete and RAC with and without Treatment or SCMs

Parameter	NA Concrete	RAC Untreated	RAC Treated + SCMs
Chloride Diffusion m^2/s (Jiang et al., 2024)	1.0×10^{-12}	$1.7–2.9 \times 10^{-12}$	$1.2–1.8 \times 10^{-12}$
Carbonation Depth 28 days (Possan et al., 2017)	5.6 mm	8.5–9.2 mm	6.3–7.0 mm
Suggested RCA (Verma et al., 2023)	—	≤30%	≤50% with SCMs

It is important for designers to use limited RCA content in the exposure classes XS1–XS3 and XC3–XC4 from EN 206, unless strong protection methods e.g., SCMs, carbonation curing, or coatings are presently used.

5.3. Freeze–Thaw Resistance and Sulfate Attack

Concrete needs to be tough against repeated pressure from nature and chemicals to last in challenging weather and difficult soil or water conditions. Because recycled aggregate concrete RAC is eco-friendly, it has characteristics that slightly alter its performance during freeze–thaw events and exposure to sulfates. The damage from freeze–thaw comes when water in the pore structure expands and breaks up the material on repeated freezing and thawing. Because of its increased porosity and ability to take up water, concrete including recycled materials is more likely to show freeze–thaw scaling and cracks. Tamayo et al., 2014 found that RAC without air entrainment loses 25–40% more mass than NAC mixes after 300 cycles. RCA is at risk of tailing when its replacement goes above 50% or when it is not saturated or pre-treated (Li et al., 2018; Xiao et al., 2019).

The presence of sulfate encourages expansive ettringite growth, which especially harms the ITZ as well as the leftover cement paste in RCA. Concretes made from RAC that was soaked in sodium sulfate solutions displayed increased expansion and a loss of compressive strength, and untreated RCA concretes showed up to a 15–25% higher expansion after six months (Xie et al., 2021).

1. Using gypsum, slag, or metakaolin to mix with the cement helps make the cement resistant to sulfate.

2. Various methods, like carbonation curing, lessen both permeability and sulfate ion penetration.

Table 9: Performance Comparison of Natural Aggregate Concrete (NAC), Untreated Recycled Aggregate Concrete (RAC), and Treated RAC with Supplementary Cementitious Materials (SCMs)

Parameter	NAC	RAC Untreated	RAC Treated + SCMs
Freeze–Thaw Scaling kg/m^2, 300 cycles	0.3–0.6	0.7–1.0	0.4–0.6
Sulfate Expansion %	<0.10%	0.13–0.18%	0.09–0.12%

5.4. Long-Term Shrinkage, Creep, and Microcracking

The deformation pattern of concrete over a long time, such as shrinkage, creep, and resulting microcracks, strongly shapes how long the construction stays durable under prolonged use. In recycled aggregate concrete RAC, these aspects are changed because recycled coarse aggregates RCA can vary in size and properties, with higher porosity and remaining cementitious materials often present in their adhered mortar (Sadati and Khayat, 2017; Chinzorigt et al., 2020; Nakararoj et al., 2022).

The majority of studies conclude that drying shrinkage in RAC can be up to 35% more than in NAC, and at 90 days after 100% RCA, strains are 850–950 micro-strain, higher than the 620–680 micro-strain strains observed in NAC. In Rachel's opinion, this happens because RCA can absorb and release more water, is very porous, and its aggregates are loosely bonded to the mortar, contributing to uneven moisture movement and damage. Using fly ash or silica fume can decrease how porous the concrete becomes and limit internal water movement. Creep increases in RAC mainly because the material has a lower modulus. The research group led by Domingo et al., 2009 saw a 30–45% greater increase in creep coefficient for RAC than for NAC in a year. Allowing creep to raise excessively can cause permanent changes and warping in built parts if it is not fixed in design. Due to the variable characteristics of RAC, all designs should be validated as being conservative. Also, less drying shrinkage tends to cause more microcracks in the transition layer, which increases the amount of permeability, carbonation, and corrosion of rebars (Helsing et al., 2024).

Table 10: Long-Term Deformation Characteristics of Natural Aggregate Concrete (NAC) and Recycled Aggregate Concrete (RAC)

Property	NAC	RAC Untreated	RAC Treated/SCM
Drying Shrinkage [με]	620–680	850–950	700–800
Creep Coefficient [-]	1.8–2.2	2.5–3.0	2.1–2.4
Microcrack Density	Low	Moderate to High	Moderate

6. Mix Design Strategies and Optimization

Optimized ways to mix recycled aggregate concretes RAC are still needed to address the variability and durability problems caused by recycled coarse aggregates RCA. Conventional concrete is different from RAC, which must address the effects of adhered mortar, needing more water and increased pores at the interfaces. The authors analyze systematically how the way mixtures are composed for RAC has developed, especially focusing on volumetric corrections, the interactions between materials, and using performance targets (Mamirov, 2021; Azhar et al., 2009).

The easiest way to use recycled coarse aggregate RCA in concrete is to put it in place of natural coarse aggregate and skip adjustments for RCA's higher water content and residual mortar. As a result, this leads to problems with pouring the concrete, excessive use of water, and less structure, so it is used for insignificant work (Fathifazl et al., 2009). Pepe et al., 2016 came up with the Equivalent Mortar Volume EMV method to handle these issues, treating RCA as a composite of its mortar and core materials, keeping constant the cement, water, and mortar content in all designs. It makes the materials more uniform, improves how strong the concrete is under load, and protects it from corrosion and strong impacts. Tests conducted by Jímenez et al., 2015 using EMV reached a sulfate resistance increase of up to 20% higher than traditional volumetric methods.

Such algorithms as the CPM and LPDM help to reduce gaps and increase particle density. They ensure the product holds together well, uses less binder, and joins the aggregates well, regardless of their sizes. Gao et al., 2023 concluded that mixtures prepared using packing models were as strong and permeable as concrete using only natural aggregate.

Volumes of silica fume 5–10%, fly ash 15–30%, and ground granulated blast furnace slag GGBFS, 20–40% are often included in RAC to improve its qualities (Qureshi et al., 2020; Fatiha et al., 2025; Robu et al., 2025). Silica fume helps with early bonding between the matrix and ITZs; fly ash raises the cement's long-term and sulfate-resistant qualities; and GGBFS is added to lower the hydration rate and lessen the chances of carbonation. Besides, superplasticizers make the concrete stronger, while admixtures decrease shrinkage and microfibers of polypropylene and steel increase how strong and crack-resistant the concrete is. Combining SCMs and fiber reinforcement in RAC showed a 14% rise in flexural strength and a 19% fall in drying shrinkage, as stated by (Jain et al., 2021).

Table 11: Comparative Evaluation of Mix Design Methods for Recycled Aggregate Concrete (RAC)

Mix Design Approach	Workability	Strength	Durability	Recommended RCA Level [%]
Volume-Based Substitution (Fathifazl et al., 2009)	Poor	Moderate	Poor	≤30
Equivalent Mortar Volume (Fathifazl et al., 2009)	Good	High	High	≤50
Particle Packing Optimization (Pepe et al., 2016)	Very Good	High	High	≤100
SCM-Enhanced Mix (Jain et al., 2021)	Good	High	Very High	≤50

7. Environmental Impact and Life Cycle Assessment (LCA)

Reducing the environmental impact of natural aggregate extraction, moving them to different sites, and disposing of them in landfills is the main reason for integrating recycled coarse aggregates RCA in concrete. Among the methods, life cycle assessment LCA offers the best way to assess these benefits at every step, starting with the beginning of a product and ending with recycling at its end (Marinkovic Mirjana et al., 2014).

A key step in conducting an LCA for concrete research is defining a functional unit FU, which helps manage how impacts are considered. Most research teams rely on

1. Concrete in one cubic meter

2. MPa on a volume of 1 m^3 of strength to ensure that their strength is similar.

It is a good choice for RAC since it ensures that products with weakened mechanical properties are still treated fairly.

Problems with how to treat RCA from demolition waste as a co-product often arise in the allocation rules used in RAC studies. ISO 14044 rules allow either option.

1. Allocation of a cut-off where no impact is assigned to RCA production,

2. Allocation of resources by the price they are sold for.

According to Kurda et al., 2018, in regions where landfill tax is high or there is more C&D waste pressure, using cut-off allocation better reflects the environmental value of RCA.

Pavements with high RCA amounts clearly lead to lower global warming potential and reduced energy use. The authors in (Zheng et al., 2025) explain that when NA is substituted for RCA by 50%, greenhouse gas emissions go down by 12–19%; yet, when also using fly ash, reductions can reach 30%.

Table 12: Environmental Impact Indicators of Different Concrete Types

Concrete Type	GWP [kg CO_2-eq/m^3]	CED [MJ/m^3]
Natural Aggregate NAC	320–360	2600–2800
RAC 50% RCA	275–300	2000–2300
RAC + SCMs	220–260	1700–2100

Concrete's natural carbonation is often not considered enough, which means concrete absorbs a portion of the CO_2 released when cement cures. RAC, because it has a high porosity and surface area, increases CO_2 uptake. Collins et al. found that, in particular when the rubble from RAC is exposed to air after being demolished, it has the potential to capture up to 15% more CO_2 over time than NAC.

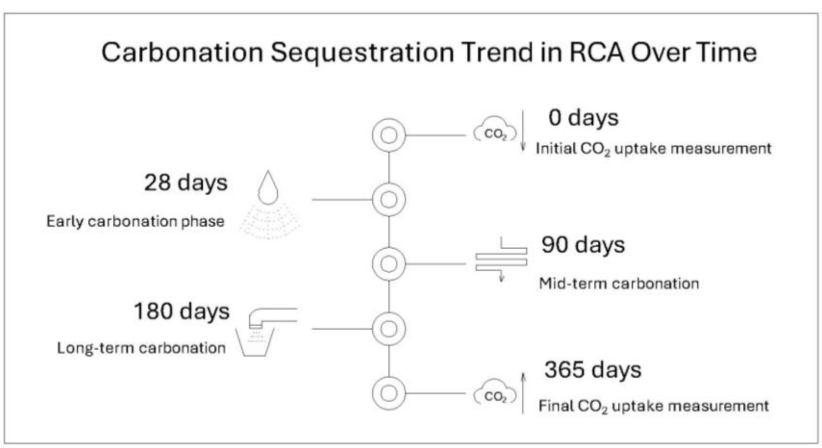

Figure 8: Carbonation Sequestration Trend of RCA

Many studies report that when the distance covered by cars is improved and the energy for treatment is decreased, RAC is more environmentally friendly. For instance:

1. Fuller et al., 2021 found that LCA-based midpoint impacts for RAC could be reduced by 22% in urban Chinese highway projects.
2. Kadawo et al., 2023 proposed a model that combines circularity index with Life Cycle Assessment to calculate how RAC contributes to sustainable outcomes in closed-loop systems.

Even though LCA creates benefits for the environment, present application of LCA to RAC still has some difficulties.

1. There is no common way to account for carbon in carbonation.
2. Different ways of distributing and naming functional units.
3. Relatively little use of end-of-life materials and second recycling.

Future LCAs should try to model types of inventories that can change, include analysis by geographic areas, and consider circular economy aspects to better stand for RAC's future ecological results.

8. Challenges and Future Directions

Since there are no common international rules for using recycled coarse aggregate RCA in concrete, its use is still limited. RCA-specific rules exist in Japan and the Netherlands; however, other countries, even emerging markets, have not yet formed clear guidelines (Wolniak et al., 2023; Soares and Tavares). Although some rules and standards do exist, for example, RILEM TC-121 and EN 12620, the lack of consistency in category systems (Polancich et al., 2014) and little code recognition still affect compliance and make buyers and engineers doubt the products (Chang et al., 2025).

Current design codes are missing important factors from RCA, like mortar and cement amounts, continuing hydration processes, and shrinkage, so updates or extra provisions are needed to handle RCA's behavior. Because engineers and developers are unsure, they tend not to use RCA in vital places such as bridges and tall buildings.

A variety within RCA's properties is caused by the source, its concrete quality, and how the buildings were manufactured. While natural aggregates average 1%, RCA water absorption can be as high as 8%; its density ranges from 2100 to 2400 kg/m^3, and its strength varies, so concrete behavior is hard to predict unless strict quality control is used (Moon et al., 2014; Obla, 2014; Shooshtarian et al., 2020). The unreliability of plastic recycling gets worse when plants use less technology without properly removing mixed materials such as gypsum, wood, and asphalt. Current guidelines, which are adapted from those for natural aggregates, do not spot the microstructural problems unique to RCAs, showing that there is a need for different testing and classifying methods (Guerra and Leite, 2021).

According to many stakeholders, such as engineers, architects, and contractors, RCA is still viewed as being of lesser quality because they have experienced excessive wear and damage with RCA in the past (Jin and Chen, 2019; Badraddin et al., 2022). Moreover, since the construction industry is not well-structured and there are issues with reporting, using best RCA practices is difficult for many (Arbuckle, 2007; Tosic et al., 2015; Wilburn and Goonan, 1998). Access to a limited number of successful cases and test results creates more uncertainty in the reliability of RCA concrete used for structures.

Even though adopting RCA is good for the environment and saves over time, there are worries about feasibility at the beginning of the project. Preparing aggregates with acid soaking, carbonation curing, or grinding usually costs more than regular aggregate preparation. Carrying rubble from demolition sites and transporting it to nearby places for recycling or use in building costs more money (Sinha et al, 2010; Makul et al., 2021; Mukal et al., 2021; Prakash et al., 2021). Since there is little support from the market in the form of policy or financial perks, it is especially difficult for public projects to use RCA (Khoury et al., 2018; Rangel et al., 2019; Ferrandez et al., 2023).

Table 13: Key Barriers to RCA Adoption and Corresponding Solutions

Barrier	Root Cause	Recommended Solution
Regulatory uncertainty (Ferrandez et al., 2023)	Lack of harmonized design codes	National standardization and international benchmarking
Quality variability (Silva et al., 2017; Brito et al., 2019)	Source heterogeneity, lack of RCA-specific specs	Treatment protocols and RCA grading systems
Industry resistance (Piccinali et al., 2025)	Negative perception and risk aversion	Demonstration projects, training, and knowledge transfer
Economic and logistical hurdles (Dinh, 2023)	High processing costs, erratic supply	Incentivization schemes, regional recycling networks

Addressing these obstacles demands using several methods together.

1. Creation of rules and enforcement for how RCA products are used (Lee et al., 2024; Saradara et al., 2024).
2. Engaging key parties through pilot projects and by assessing suppliers using lifecycle-based criteria (Alaejos et al.,2012; Hendriks, 1994; Jeon, 2024).
3. Helping recycling industries improve their quality by providing standards and certification (Buhler et al., 2023; Nassiri et al., 2025; Wang and Wu, 2023).
4. Solution providers sharing real-life results and economic impact through working closely with academics (Smical et al., 2015; Mousa, 2024).

Turning materials from recycling into standard construction inputs helps civil engineers support circular economy goals and still work with safe and reliable structures.

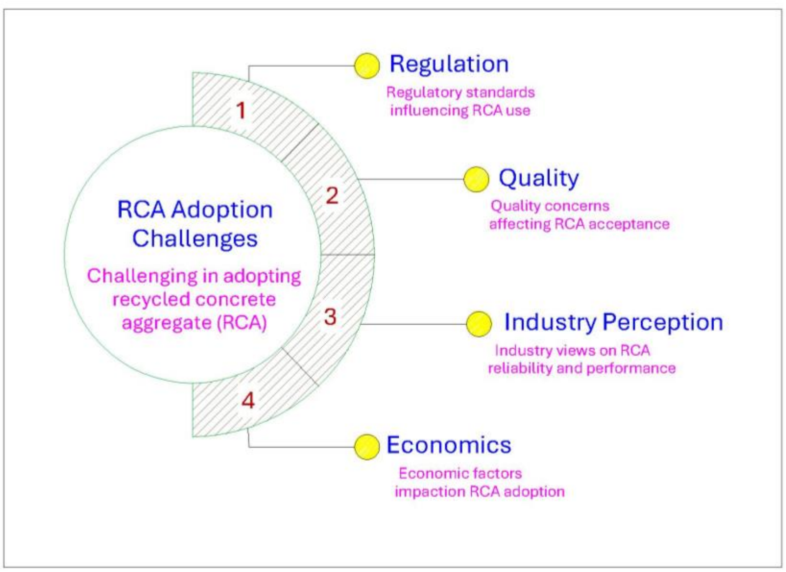

Figure 9: Adoption Challenges of RCA

9. Conclusion

- Recycled coarse aggregates RCA have the capacity to replace up to 50 % of the natural coarse aggregate with no loss of strength to 95-100 % of the control concrete when optimized through surface treatment and SCMs fly ash, silica fume, GGBS.
- RCA-SCM blends are characterized by an increase in durability, a decrease in the level of capillary absorption, a decrease in the concentration of chloride diffusion, the decrease in the depth of carbonation, and a minimal amount of freeze-thaw mass loss.
- Life-cycle assessments show global warming potential down by 15-25% and embodied energy by 18-22%; local RCA sources and the one of Equivalent Mortar Volume yield the best.
- The main obstacles are heterogeneity of the RCA properties, the absence of unified performance parameters, and economic and stakeholder limits.
- The one in the future involves formulation of performance-driven specifications, inclusion of the BIM/AI risk-driven predictive models, and enshrinement of RCA usage of circular-economy designs.
- The use of RCA-based concrete will enhance the structural durability and economical use of resources and reduce carbon impact in contemporary infrastructure.

In short, RCA-based concrete represents a safe, strong and ecologically better alternative to standard concrete. When RCA is processed, mixed optimally, and supported by regulations, it can contribute to more ecologically sound, energy-saving, and resourceful infrastructure.

Acknowledgements

The authors gratefully acknowledge KL (Deemed to be University) for providing the necessary facilities and institutional support to carry out this research work.

Author Contributions

S.T. conceived and designed the study. **L.N.** conducted experiments and collected the data. **S.T.** also performed statistical analysis and contributed to data interpretation and manuscript drafting. All authors critically reviewed and approved the final version of the manuscript and agreed to be accountable for all aspects of the work.

Disclosure of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

References

Barbuta, M., Bucur, R. D., Cimpeanu, S. M., Paraschiv, G., & Bucur, D. (2015). Wastes in building materials industry. Agroecology, 1(1), 81–99.

Davidovits, J. (1994). Global warming impact on the cement and aggregates industries. World Resource Review, 6(2), 263–278.

Prikryl, R. (2021). Geomaterials as construction aggregates: A state-of-the-art. Bulletin of Engineering Geology and the Environment, 80, 8831–8845.

De Brito, J., & Saikia, N. (2012). Recycled aggregate in concrete: Use of industrial, construction, and demolition waste. Springer Science & Business Media.

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

Naik, T. R., & Moriconi, G. (2005, October). Environmental-friendly durable concrete made with recycled materials for sustainable concrete construction. Paper presented at the International Symposium on Sustainable Development of Cement, Concrete and Concrete Structures, Toronto, Ontario.

Kashkash, S. (2024). Sustainable recycled structural concrete design incorporating recycled coarse aggregate (Master's thesis). University of Pecs, Hungary.

Fort, J., Afolayan, A., Koci, V., Scheinherrova, L., Jan, J., Borovec, J., & Cerny, R. (2024). Potential of water sediments in construction materials: Current approaches and critical consideration of future challenges. Heliyon.

Da, S., & Le Billon, P. (2022). Sand mining: Stopping the grind of unregulated supply chains. Extractive Industries and Society, 10, 101070.

Shamoon, A., Haleem, A., Bahl, S., Javaid, M., Garg, S. B., Sharma, R. C., & Garg, J. (2022). Environmental impact of energy production and extraction of materials: A review. Materials Today: Proceedings, 57, 936–941.

Lu, C., & Wang, K. (2023). Natural resource conservation outpaces and climate change: Roles of reforestation, mineral extraction, and natural resources depletion. Resources Policy, 86, 104159. https://doi.org/10.1016/j.resourpol.2023.104159

Zheng, L., Wu, H., Zhang, H., Duan, H., Wang, J., Jiang, W., Dong, B., Liu, G., Zuo, J., & Song, Q. (2017). Characterizing the generation and flows of construction and demolition waste in China. Construction and Building Materials, 136, 405–413. https://doi.org/10.1016/j.conbuildmat.2017.01.081

Bao, Z., & Lu, W. (2020). Developing efficient circularity for construction and demolition waste management in fast emerging economies: Lessons learned from Shenzhen, China. Science of the Total Environment, 724, 138264. https://doi.org/10.1016/j.scitotenv.2020.138264

Jain, S., Singhal, S., & Jain, N. K. (2021). Construction and demolition waste (C&DW) in India: Generation rate and implications of C&DW recycling. International Journal of Construction Management, 21(3), 261–270. https://doi.org/10.1080/15623599.2019.1602527

Saez, P. V., & Osmani, M. (2019). A diagnosis of construction and demolition waste generation and recovery practice in the European Union. Journal of Cleaner Production, 241, 118400. https://doi.org/10.1016/j.jclepro.2019.118400

Iacoboaea, C., Aldea, M., & Petrescu, F. (2019). Construction and demolition waste - A challenge for the European Union. Theoretical and Empirical Research in Urban Management, 14(1), 30–52. https://doi.org/10.2139/ssrn.3386317

Jain, M. S. (2021). A mini review on generation, handling, and initiatives to tackle construction and demolition waste in India. Environmental Technology & Innovation, 22, 101490. https://doi.org/10.1016/j.eti.2021.101490

Duan, H., Miller, T. R., Liu, G., & Tam, V. W. Y. (2019). Construction debris becomes growing concern of growing cities. Waste Management, 83, 1–5. https://doi.org/10.1016/j.wasman.2018.11.022

Siddiqua, A., Hahladakis, J. N., & Al-Attiya, W. A. K. (2022). An overview of the environmental pollution and health effects associated with waste landfilling and open dumping. Environmental Science and Pollution Research, 29(39), 58514–58536. https://doi.org/10.1007/s11356-022-19971-5

Fazzo, L., Manno, V., Iavarone, I., Minelli, G., De Santis, M., Beccaloni, E., Scaini, F., Miotto, E., Airoma, D., & Comba, P. (2023). The health impact of hazardous waste landfills and illegal dumps contaminated sites: An epidemiological study at ecological level in Italian Region. Frontiers in Public Health, 11, 996960. https://doi.org/10.3389/fpubh.2023.996960

Vahidi, A., Mostaani, A., Gebremariam, A. T., Di Maio, F., & Rem, P. (2024). Feasibility of utilizing recycled coarse aggregates in commercial concrete production. Journal of Cleaner Production, 474, 143578. https://doi.org/10.1016/j.jclepro.2023.143578

Xu, X., Luo, Y., Sreeram, A., Wu, Q., Chen, G., Cheng, S., Chen, Z., & Chen, X. (2022). Potential use of recycled concrete aggregate (RCA) for sustainable asphalt pavements of the future: A state-of-the-art review. Journal of Cleaner Production, 344, 130893. https://doi.org/10.1016/j.jclepro.2022.130893

Hendriks, C. A., Worrell, E., De Jager, D., Blok, K., & Riemer, P. (1998). Emission reduction of greenhouse gases from the cement industry. In Proceedings of the Fourth International Conference on Greenhouse Gas Control Technologies (pp. 939–944). IEA GHG R&D Programme.

Akan, M. O. A., Dhavale, D. G., & Sarkis, J. (2017). Greenhouse gas emissions in the construction industry: An analysis and evaluation of a concrete supply chain. Journal of Cleaner Production, 167, 1195–1207. https://doi.org/10.1016/j.jclepro.2017.08.155

Bexell, M., & Jönsson, K. (2017). Responsibility and the United Nations' sustainable development goals. In Forum for Development Studies (pp. 13–29). Taylor & Francis. https://doi.org/10.1080/08039410.2017.1304677

Sabai, M. M. (2013). Construction and demolition waste recycling into innovative building materials for sustainable construction in Tanzania (Master's thesis).

Richardson, A. (2013). Recycled materials in concrete. In Reuse of materials and byproducts in construction: Waste minimization and recycling (pp. 67–109). Springer.

Kadawo, A., Sadagopan, M., During, O., Bolton, K., & Nagy, A. (2023). Combination of LCA and circularity index for assessment of environmental impact of recycled aggregate concrete. Journal of Sustainable Cement-Based Materials, 12(1), 1–12.

Roh, S., Kim, R., Park, W.J., & Ban, H. (2020). Environmental evaluation of concrete containing recycled and by-product aggregates based on life cycle assessment. Applied Sciences, 10(21), 7503.

Prasittisopin, L., Tuvayanond, W., Kang, T. H.K., & Kaewunruen, S. (2025). Concrete mix design of recycled concrete aggregate (RCA): Analysis of review papers, characteristics, research trends, and underexplored topics. Resources, 14(2), 21.

Suaiam, G., & Makul, N. (2024). Potential future direction of the sustainable production of precast concrete with recycled concrete aggregate: A critical review. Engineering Science, 28, 1075.

Al-Otaibi, A. (2024). Barriers and enablers for green concrete adoption: A scientometric aided literature review approach. Sustainability, 16(12), 5093.

Mahmoud, A. S., & Omar, A. S. (2024). Recycled concrete aggregates utilization in construction: Publications trends, bibliometric analysis, and literature review (2011–2021). Journal of Scientometric Research, 13(3), 757–772.

Han, S., Zhao, S., Lu, D., & Wang, D. (2023). Performance improvement of recycled concrete aggregates and their potential applications in infrastructure: A review. Buildings, 13(6), 1411.

Kluppel, H. J. (1998). ISO 14041: Environmental management life cycle assessment goal and scope definition inventory analysis. International Journal of Life Cycle Assessment, 3(6), 301. https://doi.org/10.1007/bf02979337

Falagas, M. E., Pitsouni, E. I., Malietzis, G. A., & Pappas, G. (2008). Comparison of PubMed, Scopus, Web of Science, and Google Scholar: Strengths and weaknesses. FASEB Journal, 22(2), 338–342.

Wang, Q., & Waltman, L. (2016). Large-scale analysis of the accuracy of the journal classification systems of Web of Science and Scopus. Journal of Informetrics, 10(2), 347–364.

Srour, I. M., Chehab, G. R., El-Fadel, M., & Tamraz, S. (2013). Pilot-based assessment of the economics of recycling construction demolition waste. Waste Management & Research, 31(11), 1170–1179.

Yuan, H. (2017). Barriers and countermeasures for managing construction and demolition waste: A case of Shenzhen in China. Journal of Cleaner Production, 157, 84–93. https://doi.org/10.1016/j.jclepro.2017.04.137

Seto, K. E., Churchill, C. J., & Panesar, D. K. (2017). Influence of fly ash allocation approaches on the life cycle assessment of cement-based materials. Journal of Cleaner Production, 157, 65–75.

Rodrigues, F. A., & Joekes, I. (2011). Cement industry: Sustainability, challenges and perspectives. Environmental Chemistry Letters, 9, 151–166.

Zhou, X., Lu, D., Du, X., Wang, G., & Meng, F. (2020). A 3D non-orthogonal plastic damage model for concrete. Computer Methods in Applied Mechanics and Engineering, 360, 112716.

Wongkvanklom, A., Posi, P., Khotsopha, B., Ketmala, C., Pluemsud, N., Lertnimoolchai, S., & Chindaprasirt, P. (2018). Structural lightweight concrete containing recycled lightweight concrete aggregate. KSCE Journal of Civil Engineering, 22(8), 3077–3084.

De Schepper, M., Van den Heede, P., Van Driessche, I., & De Belie, N. (2014). Life cycle assessment of completely recyclable concrete. Materials (Basel), 7(8), 6010–6027.

Ghoshal, S., & Zeman, F. (2010). Carbon dioxide (CO2) capture and storage technology in the cement and concrete industry. In Developments and innovation in carbon dioxide (CO2) capture and storage technology (pp. 469–491). Elsevier.

Wu, B., Zhao, X.-Y., Zhang, J.-S., & Yang, Y. (2013). Cyclic testing of thin-walled circular steel tubular columns filled with demolished concrete blocks and fresh concrete. Thin-Walled Structures, 66, 50–61.

Butera, S., Christensen, T. H., & Astrup, T. F. (2015). Life cycle assessment of construction and demolition waste management. Waste Management, 44, 196–205.

Ayub, T., Mahmood, W., & Khan, A.-R. (2021). Durability performance of SCC and SCGC containing recycled concrete aggregates: A comparative study. Sustainability, 13(15), 8621.

Bandeira, S. R., Maciel, J. B. S., Carlos, J., de Oliveira, S., & Sanches, A. E. (n.d.). Construction and demolition waste management practices at construction sites.

Jin, Z., Li, M., Pang, B., Yang, L., Chen, Y., & Wang, D. (2024). Internal superhydrophobic marine concrete: Interface modification based on slag microstructure regulation. Journal of Building Engineering, 86, 108769.

Epstein, M. J. (2018). Making sustainability work: Best practices in managing and measuring corporate social, environmental and economic impacts. Routledge.

Oyedele, L. O., Regan, M., Von Meding, J., Ahmed, A., Ebohon, O. J., & Elnokaly, A. (2013). Reducing waste to landfill in the UK: Identifying impediments and critical solutions. World Journal of Science, Technology and Sustainable Development, 10(2), 131–142.

Serres, N., Braymand, S., & Feugeas, F. (2016). Environmental evaluation of concrete made from recycled concrete aggregate implementing life cycle assessment. Journal of Building Engineering, 5, 24–33.

Won, J., Cheng, J. C. P., & Lee, G. (2016). Quantification of construction waste prevented by BIM-based design validation: Case studies in South Korea. Waste Management, 49, 170–180.

Teh, S. H., Wiedmann, T., Castel, A., & de Burgh, J. (2017). Hybrid life cycle assessment of greenhouse gas emissions from cement, concrete and geopolymer concrete in Australia. Journal of Cleaner Production, 152, 312–320.

Khanh, H. D., & Kim, S. Y. (2015). Development of waste occurrence level indicator in Vietnam construction industry. Engineering, Construction and Architectural Management, 22(6), 715–731.

Lu, W., Chen, X., Peng, Y., & Liu, X. (2018). The effects of green building on construction waste minimization: Triangulating 'big data' with 'thick data'. Waste Management, 79, 142–152.

Van der Zee, S., & Zeman, F. (2016). Production of carbon negative precipitated calcium carbonate from waste concrete. Canadian Journal of Chemical Engineering, 94(11), 2153–2159.

Jin, R., Li, B., Zhou, T., Wanatowski, D., & Piroozfar, P. (2017). An empirical study of perceptions towards construction and demolition waste recycling and reuse in China. Resources, Conservation & Recycling, 126, 86–98.

Colangelo, F., Petrillo, A., Cioffi, R., Borrelli, C., & Forcina, A. (2018). Life cycle assessment of recycled concretes: A case study in southern Italy. Science of The Total Environment, 615, 1506–1517.

Borghi, G., Pantini, S., & Rigamonti, L. (2018). Life cycle assessment of non-hazardous construction and demolition waste (CDW) management in Lombardy Region (Italy). Journal of Cleaner Production, 184, 815–825.

Ramanathan, P., Baskar, I., Muthupriya, P., & Venkatasubramani, R. (2013). Performance of self-compacting concrete containing different mineral admixtures. KSCE Journal of Civil Engineering, 17(2), 465–472.

Mohseni, E., Saadati, R., Kordbacheh, N., Parpinchi, Z. S., & Tang, W. (2017). Engineering and microstructural assessment of fibre-reinforced self-compacting concrete containing recycled coarse aggregate. Journal of Cleaner Production, 168, 605–613.

Mohan, A., & Mini, K. M. (2018). Strength and durability studies of SCC incorporating silica fume and ultra-fine GGBS. Construction and Building Materials, 171, 919–928.

Fang, B., Qian, Z., Song, Y., Diao, X., Shi, T., Cai, X., & Wang, L. (2024). Evaluation of early crack resistance performance of concrete mixed with ternary minerals using temperature stress testing machine (TSTM). Journal of Cleaner Production, 465, 142780.

Jimenez, C., Barra, M., Josa, A., & Valls, S. (2015). LCA of recycled and conventional concretes designed using the Equivalent Mortar Volume and classic methods. Construction and Building Materials, 84, 245–252.

Wei, C., Li, Y., Liu, X., Zhang, Z., Wu, P., & Gu, J. (2024). Large-scale application of coal gasification slag in non-burnt bricks: Hydration characteristics and mechanism analysis. Construction and Building Materials, 421, 135674.

Wu, B., Liu, C., & Wu, Y. (2014). Compressive behaviors of cylindrical concrete specimens made of demolished concrete blocks and fresh concrete. Construction and Building Materials, 53, 118–130.

Dos Reis, G. S., Quattrone, M., Ambrós, W. M., Cazacliu, B. G., & Hoffmann Sampaio, C. (2021). Current applications of recycled aggregates from construction and demolition: A review. Materials (Basel), 14(7), 1700.

Ahmed, H., Tiznobaik, M., Huda, S. B., Islam, M. S., & Alam, M. S. (2020). Recycled aggregate concrete from large-scale production to sustainable field application. Construction and Building Materials, 262, 119979.

Majhi, R. K., Nayak, A. N., & Mukharjee, B. B. (2018). Development of sustainable concrete using recycled coarse aggregate and ground granulated blast furnace slag. Construction and Building Materials, 159, 417–430.

Ulsen, C., Tseng, E., Angulo, S. C., Landmann, M., Contessotto, R., Balbo, J. T., & Kahn, H. (2019). Concrete aggregates properties crushed by jaw and impact secondary crushing. Journal of Materials Research and Technology, 8(1), 494–502.

Djamarani, K. M., & Clark, I. M. (1997). Characterization of particle size based on fine and coarse fractions. Powder Technology, 93(2), 101–108.

Ivanovskis, L. (2019). Systematic selection of perspective solid waste mechanical separation technologies for material recovery.

Ouyang, K., Liu, J., Liu, S., Song, B., Guo, H., Li, G., & Shi, C. (2023). Influence of pre-treatment methods for recycled concrete aggregate on the performance of recycled concrete: A review. Resources, Conservation & Recycling, 188, 106717.

Verma, A., Velaga, B. S., & Arunachalam, S. (2023). Performance evaluation of concrete using treated recycled aggregates modified with mineral admixtures: Influence of processing. European Journal of Environmental and Civil Engineering, 27(3), 1010–1039.

De Brito, J., & Saikia, N. (2013). Concrete with recycled aggregates in international codes. In Recycled aggregates concrete use in industrial construction and demolition waste (pp. 379–429).

Kazemian, F., Rooholamini, H., & Hassani, A. (2019). Mechanical and fracture properties of concrete containing treated and untreated recycled concrete aggregates. Construction and Building Materials, 209, 690–700.

Kurda, R., Silvestre, J. D., & de Brito, J. (2018). Life cycle assessment of concrete made with high volume of recycled concrete aggregates and fly ash. Resources, Conservation & Recycling, 139, 407–417.

Tam, V. W. Y., Tam, C. M., & Le, K. N. (2007). Removal of cement mortar remains from recycled aggregate using pre-soaking approaches. Resources, Conservation & Recycling, 50(1), 82–101.

He, H., Zhang, C., Yang, J., Li, M., Fu, W., Senetakis, K., Zhang, D., & Liu, S. (2023). Characterization of recycled concrete aggregate (RCA) particles for geotechnical engineering applications: Particle strength and interparticle contact behavior. Construction and Building Materials, 407, 133532.

Rahal, K. N. (2007). Mechanical properties of concrete with recycled coarse aggregate. Building and Environment, 42(1), 407–415. https://doi.org/10.1016/j.buildenv.2005.07.033

Liang, C., You, J., Gu, F., Gao, Y., Yang, G., He, Z., Hou, S., & Duan, Z. (2022). Enhancing the elastic modulus of concrete prepared with recycled coarse aggregates of different quality by chemical modifications. Construction and Building Materials, 360, 129590.

Alengaram, U. J., Salam, A., Jumaat, M. Z., Jaafar, F. F., & Saad, H. B. (2011). Properties of high-workability concrete with recycled concrete aggregate. Materials Research, 14, 248–255.

Thomas, J., Thaickavil, N. N., & Wilson, P. M. (2018). Strength and durability of concrete containing recycled concrete aggregates. Journal of Building Engineering, 19, 349–365.

Butler, L., West, J. S., & Tighe, S. L. (2011). The effect of recycled concrete aggregate properties on the bond strength between RCA concrete and steel reinforcement. Cement and Concrete Research, 41(10), 1037–1049.

Ismail, S., & Ramli, M. (2013). Engineering properties of treated recycled concrete aggregate (RCA) for structural applications. Construction and Building Materials, 44, 464–476.

Fernandes, B., Carré, H., Mindeguia, J.-C., Perlot, C., & La Borderie, C. (2021). Effect of elevated temperatures on concrete made with recycled concrete aggregates: An overview. Journal of Building Engineering, 44, 103235.

Pliya, P., Cree, D., Hajiloo, H., Beaucour, A.-L., Green, M. F., & Noumowé, A. (2019). High-strength concrete containing recycled coarse aggregate subjected to elevated temperatures. Fire Technology, 55, 1477–1494.

Leite, M. B., & Monteiro, P. J. M. (2016). Microstructural analysis of recycled concrete using X-ray microtomography. Cement and Concrete Research, 81, 38–48.

Panghal, H., & Kumar, A. (2024). Recycled coarse aggregates in concrete: A comprehensive study of mechanical and microstructural properties. Iranian Journal of Science and Technology, Transactions of Civil Engineering, 1–17.

Bansal, S., Choudhary, L., Kalra, M., Dave, N., & Sharma, A. K. (2025). Mechanical and microstructural characteristics of structural concrete containing RCA treated with sodium metasilicate. Journal of Engineering Design and Technology, 23(3), 854–870.

Yang, X., Liu, Y., Liang, J., Meng, Y., Rong, H., Li, D., Chen, Y., Lv, J., Jiang, Y., & Liu, Y. (2023). Straightening methods for RCA and RAC—A review. Cement and Concrete Composites, 141, 105145.

Nikmehr, B., Kafle, B., & Al-Ameri, R. (2024). A review of the advanced treatment techniques for enriching the recycled concrete aggregates for recycled-based concrete: Economic, environmental and technical analysis. Smart and Sustainable Built Environment, 13(3), 560–583.

Alqarni, A. S., Abbas, H., Al-Shwikh, K. M., & Al-Salloum, Y. A. (2021). Treatment of recycled concrete aggregate to enhance concrete performance. Construction and Building Materials, 307, 124960.

Savva, P., Ioannou, S., Oikonomopoulou, K., Nicolaides, D., & Petrou, M. F. (2021). A mechanical treatment method for recycled aggregates and its effect on recycled aggregate-based concrete. Materials (Basel), 14(9), 2186.

Atmajayanti, A. T., & Haryanto, Y. (2018). The effect of recycled coarse aggregate (RCA) with surface treatment on concrete mechanical properties. In MATEC Web of Conferences (p. 1017). EDP Sciences.

Forero, J. A., de Brito, J., Evangelista, L., & Pereira, C. (2022). Improvement of the quality of recycled concrete aggregate subjected to chemical treatments: A review. Materials (Basel), 15(8), 2740.

Yunusa, M., Zhang, X., Cui, P., & Tian, X. (2022). Durability of recycled concrete aggregates prepared with mechanochemical and thermal treatment. Materials (Basel), 15(16), 5792.

Al-Bayati, H. K. A., Das, P. K., Tighe, S. L., & Baaj, H. (2016). Evaluation of various treatment methods for enhancing the physical and morphological properties of coarse recycled concrete aggregate. Construction and Building Materials, 112, 284–298.

Farahani, H. S., Zadeh, A. H., Hu, J., Hawkins, C., & Kim, S. (2025). Carbonation reaction of recycled concrete aggregates (RCA): CO_2 mass consumption under various treatment conditions. Cleaner Materials, 15, 100296.

Li, L., & Wu, M. (2022). An overview of utilizing CO_2 for accelerated carbonation treatment in the concrete industry. Journal of CO_2 Utilization, 60, 102000.

Pallapothu, S. N. R. G., Pancharathi, R. K., & Midathada, L. (2024). Integrating particle packing approach with machine learning techniques to optimise the compressive strength of RCA-based concrete mixes. Journal of Building Engineering, 94, 109994.

Tamayo, P., Pacheco, J., Thomas, C., de Brito, J., & Rico, J. (2019). Mechanical and durability properties of concrete with coarse recycled aggregate produced with electric arc furnace slag concrete. Applied Sciences, 10(1), 216.

Tamayo Castañeda, P., Pacheco, J., Thomas García, C., de Brito, J., & Rico Arenal, J. (2020). Mechanical and durability properties of concrete with coarse recycled aggregate produced with electric arc furnace slag concrete.

Xiao, J., & Zhang, C. (2006). On relationships between the mechanical properties of recycled aggregate concrete: An overview. Materials and Structures, 39(6), 655–664. https://doi.org/10.1617/s11527-006-9093-0

Butler, L., West, J. S., & Tighe, S. L. (2013). Effect of recycled concrete coarse aggregate from multiple sources on the hardened properties of concrete with equivalent compressive strength. Construction and Building Materials, 47, 1292–1301.

Choubey, R. K., Kumar, S., & Rao, M. C. (2016). Modeling of fracture parameters for crack propagation in recycled aggregate concrete. Construction and Building Materials, 106, 168–178.

Moolaei, S., Sharbatdar, M. K., & Kheyroddin, A. (2021). Experimental evaluation of flexural behavior of HPFRCC beams reinforced with hybrid steel and GFRP bars. Composite Structures, 275, 114503.

Hossain, F. M. Z. (2024). Mechanical and structural behaviour of rubberised recycled aggregate concrete (Doctoral dissertation). University of British Columbia (Okanagan).

Alibeigibeni, F., Stochino, F., & Zucca, M. (2025). Enhancing concrete sustainability: A critical review of the performance of recycled concrete aggregates (RCAs) in structural concrete. Buildings, 15(8), 1–25.

Wu, Z., Xu, J., Zhong, J., Liu, Q., & Liu, W. (2011). Behavior of reinforced concrete beams filled with demolished concrete lumps. Structural Engineering and Mechanics, 40(3), 411–429. https://doi.org/10.12989/sem.2011.40.3.411

Peng, Q., Wang, L., & Lu, Q. (2018). Influence of recycled coarse aggregate replacement percentage on fatigue performance of recycled aggregate concrete. Construction and Building Materials, 169, 347–353.

Immelman, D. W. (2013). The influence of percentage replacement on the aggregate and concrete properties from commercially produced coarse recycled concrete aggregate (Master's thesis). Stellenbosch University.

Singh, G. (2021). Influence of partial replacement of RCA on properties of concrete. Materials Today: Proceedings, 37, 2432–2438.

Cui, H. Z., Shi, X., Memon, S. A., Xing, F., & Tang, W. (2015). Experimental study on the influence of water absorption of recycled coarse aggregates on properties of the resulting concretes. Journal of Materials in Civil Engineering, 27(4), 04014138.

Lin, L., & Wu, B. (2022). Water permeability behavior of recycled lump/aggregate concrete. Construction and Building Materials, 323, 126508.

Al-Ghalibi, E. A. M., & Mohamad, S. A. (2021). Evaluate the durability and effect of water absorption of recycled aggregate used in pavement. Materials Today: Proceedings, 42, 2561–2565.

Dimitriou, G., Savva, P., & Petrou, M. F. (2018). Enhancing mechanical and durability properties of recycled aggregate concrete. Construction and Building Materials, 158, 228–235.

Possan, E. A. T., Aleandri, G. A., Felix, E. F., & dos Santos, A. C. P. (2017). CO_2 uptake potential due to concrete carbonation: A case study. Case Studies in Construction Materials, 6, 147–161. https://doi.org/10.1016/j.cscm.2017.01.007

Jiang, H., Wu, L., Guan, L., Liu, M., Ju, X., Xiang, Z., Jiang, X., Li, Y., & Long, J. (2024). Durability life evaluation of marine infrastructures built using carbonated recycled coarse aggregate concrete under chloride corrosive environment. Frontiers in Marine Science, 11, 1357186.

Li, Y., Wang, R., Li, S., Zhao, Y., & Qin, Y. (2018). Resistance of recycled aggregate concrete containing low- and high-volume fly ash against the combined action of freeze–thaw cycles and sulfate attack. Construction and Building Materials, 166, 23–34.

Xiao, Q. H., Cao, Z. Y., Guan, X., Li, Q., & Liu, X. L. (2019). Damage to recycled concrete with different aggregate substitution rates from the coupled action of freeze–thaw cycles and sulfate attack. Construction and Building Materials, 221, 74–83.

Xie, F., Li, J., Zhao, G., Wang, C., Wang, Y., & Zhou, P. (2021). Experimental investigations on the durability and degradation mechanism of cast-in-situ recycled aggregate concrete under chemical sulfate attack. Construction and Building Materials, 297, 123771.

Sadati, S., & Khayat, K. H. (2017). Restrained shrinkage cracking of recycled aggregate concrete. Materials and Structures, 50, 1–15.

Chinzorigt, G., Lim, M. K., Yu, M., Lee, H., Enkbold, O., & Choi, D. (2020). Strength, shrinkage, creep, and durability aspects of concrete including CO_2-treated recycled fine aggregate. Cement and Concrete Research, 136, 106062.

Nakararoj, N., Tran, T. N. H., Sukontasukkul, P., Attachaiyawuth, A., Tangchirapat, W., Ban, C. C., Rattanachu, P., & Jaturapitakkul, C. (2022). Effects of high-volume bottom ash on strength, shrinkage, and creep of high-strength recycled aggregate concrete. Construction and Building Materials, 356, 129233.

Domingo, L., Gayarre, F. L., Serrano, M. A., & López-Colina, C. (2009). Long-term deformations by creep and shrinkage in recycled aggregate concrete. Materials and Structures, 43(8), 1147–1160. https://doi.org/10.1617/s11527-009-9573-0

Helsing, E., Brander, L., & Martinsson, P. (2024). Durability of concrete with recycled aggregate. Nordic Concrete Research, 71(1), 69–89. https://doi.org/10.2478/ncr-2024-0014

Mamirov, M. (2021). A comprehensive analysis of recycled concrete aggregate (RCA) characteristics and effective use of RCA characteristics in concrete mixture design (Doctoral dissertation). University of Nebraska–Lincoln.Azhar, K. M., Elliott, R. J. R., & Violet, T. M. H. (2009). On volume-based measures of revealed comparative

advantage: An empirical test for ASEAN. In Proceedings of the International Conference on Globalization, Growth and Development in Asia (January 14–15). University of Nottingham Malaysia, Kuala Lumpur.

Fathifazl, G. A., Razaqpur, A. G., Isgor, O. B., Fournier, B., & Foo, S. (2009). New mixture proportioning method for concrete made with coarse recycled concrete aggregate. Journal of Materials in Civil Engineering, 21(10), 601–611. https://doi.org/10.1061/(ASCE)0899-1561(2009)21:10(601)

Pepe, M. F., Toledo, R. D., Koenders, E. A. B., & Martinelli, E. (2016). A novel mix design methodology for recycled aggregate concrete. Construction and Building Materials, 122, 362–372. https://doi.org/10.1016/j.conbuildmat.2016.06.061

Gao, S., Guo, X., Ban, S., Ma, Y., Yu, Q., & Sui, S. (2023). Influence of supplementary cementitious materials on ITZ characteristics of recycled concrete. Construction and Building Materials, 363, 129736.

Qureshi, L. A., Ali, B., & Ali, A. (2020). Combined effects of supplementary cementitious materials (silica fume, GGBS, fly ash, and rice husk ash) and steel fiber on the hardened properties of recycled aggregate concrete. Construction and Building Materials, 263, 120636.

Fatiha, E., Karim, E., Mhamed, A., & Abed, F. (2025). Enhancing performance of recycled aggregate concrete with supplementary cementitious materials. Cleaner Materials, 15, 100298.

Robu, I., Mazilu, C., & Deju, R. (2016). Study concerning characterization of some recycled concrete aggregates. Scientific Journal: Series Mathematical Modelling in Civil Engineering, 12(1), 1–12. https://doi.org/10.1515/mmce-2016-0001

Marinković, S. M., & Ignjatović, I. (2014). Life cycle assessment (LCA) of concrete made using recycled concrete or natural aggregates. In Eco-efficient construction and building materials (pp. 239–266). Elsevier. https://doi.org/10.1533/9780857097729.2.239

Zheng, Y., Qian, L., Zhou, L., Gao, F., Deng, Z., Wang, J., Guo, Z., & Ding, H. (2025). Life cycle assessment and life cycle cost analysis of sustainable concrete incorporating recycled aggregates. Sustainability, 17(5), 1779.

Fuller, H. J. A., Arnold, T., & Bagian, T. M. (2021). Learning from root cause analysis (RCA) actions that use standardization to address patient safety concerns. In Proceedings of the International Symposium on Human Factors and Ergonomics in Health Care (pp. 281–285). SAGE Publications.

Wolniak, R., Gajdzik, B., & Grebski, W. (2023). The usage of root cause analysis (RCA) in Industry 4.0 conditions. Zeszyty Naukowe Politechniki Śląskiej. Organizacja i Zarządzanie, 190, 223–235.

Soares, C. M., & Tavares, M. E. N. (n.d.). Concretes with recycled masonry aggregates. SSRN. https://ssrn.com/abstract=4252430

Polancich, S., Roussel, L., & Patrician, P. (2014). Best practices for conducting a root cause analysis: Are there any? Patient Safety & Quality Healthcare.

Chang, C., Di Maio, F., Bheemireddy, R., Posthoorn, P., Gebremariam, A. T., & Rem, P. (2025). Rapid quality control for recycled coarse aggregates (RCA) streams: Multi-sensor integration for advanced contaminant detection. Computers in Industry, 164, 104196. https://doi.org/10.1016/j.compind.2024.104196

Moon, S., Zekavat, P. R., & Bernold, L. E. (2017). Dynamic quality control of process resources to improve concrete supply chain. Journal of Construction Engineering and Management, 143(5), 04016130.

Obla, K. H. (2014). Improving concrete quality. CRC Press.

Shooshtarian, S., Caldera, S., Maqsood, T., & Ryley, T. (2020). Using recycled construction and demolition waste products: A review of stakeholders' perceptions, decisions, and motivations. Recycling, 5(4), 31.

Guerra, B. C., & Leite, F. (2021). Circular economy in the construction industry: An overview of United States stakeholders' awareness, major challenges, and enablers. Resources, Conservation & Recycling, 170, 105617.

Jin, R., & Chen, Q. (2019). Overview of concrete recycling legislation and practice in the United States. Journal of Construction Engineering and Management, 145(4), 05019004.

Badraddin, K., Radzi, A. R., Almutairi, S., & Rahman, R. A. (2022). Critical success factors for concrete recycling in construction projects. Sustainability, 14(5), 3102.

Arbuckle, P. (2007). Discovering institutional barriers and opportunities for sustainable concrete construction.

Tošić, N., Marinković, S., Dašić, T., & Stanić, M. (2015). Multicriteria optimization of natural and recycled aggregate concrete for structural use. Journal of Cleaner Production, 87, 766–776.

Wilburn, D. R., & Goonan, T. G. (1998). Aggregates from natural and recycled sources (U.S. Geological Survey Circular 1176). U.S. Geological Survey.

Sinha, S., Shankar, R., & Taneerananon, P. (2010). Modelling and case study of reverse logistics for construction aggregates. International Journal of Logistics Systems and Management, 6(1), 39–59.

Makul, N., Fediuk, R., Amran, M., Zeyad, A. M., de Azevedo, A. R. G., Klyuev, S., Vatin, N., & Karelina, M. (2021). Capacity to develop recycled aggregate concrete in South East Asia. Buildings, 11(6), 234.

Makul, N., Fediuk, R., Amran, M., Zeyad, A. M., Klyuev, S., Chulkova, S., Ozbakkaloglu, I., Vatin, T., Karelina, M., & Azevedo, A. (2021). Design strategy for recycled aggregate concrete: A review of status and future perspectives. Crystals, 11(6), 695.

Prakash, S., Wijayasundara, M., Pathirana, P. N., & Law, K. (2021). De-risking resource recovery value chains for a circular economy: Accounting for supply and demand variations in recycled aggregate concrete. Resources, Conservation & Recycling, 168, 105312.

Khoury, E., Ambrós, W., Cazacliu, B., Sampaio, C. H., & Remond, S. (2018). Heterogeneity of recycled concrete aggregates: An intrinsic variability. Construction and Building Materials, 175, 705–713.

Rangel, C. S., Toledo Filho, R. D., Amario, M., Pepe, M., de Castro Polisseni, G., & de Andrade, G. P. (2019). Generalized quality control parameter for heterogeneous recycled concrete aggregates: A pilot-scale case study. Journal of Cleaner Production, 208, 589–601.

Ferrandez, D., Saiz, P., Zaragoza-Benzal, A., & Zúñiga-Vicente, J. A. (2023). Towards a more sustainable environmentally friendly production system for the treatment of recycled aggregates in the construction industry: An experimental study. Heliyon, 9(6).

Silva, R. V., de Brito, J., & Dhir, R. K. (2017). Availability and processing of recycled aggregates within the construction and demolition supply chain: A review. Journal of Cleaner Production, 143, 598–614.

de Brito, J., Agrela, F., & Silva, R. V. (2019). Legal regulations of recycled aggregate concrete in buildings and roads. In New trends in eco-efficient and recycled concrete (pp. 509–526). Elsevier.

Piccinali, A., Abbà, A., Galvin, A. P., Plizzari, G., & Sorlini, S. (2025). The contamination levels of recycled aggregates from construction and demolition waste in compliance with Italian and Spanish regulations. Environmental Science and Pollution Research, 1–14.

Dinh, T. H. (2023). Life cycle sustainability assessment for selecting construction materials in the preliminary design phase of road construction projects.

Lee, P. H., Han, Q., & de Vries, B. (2024). Advancing a sustainable built environment: A comprehensive review of stakeholder promotion strategies and dual forces. Journal of Building Engineering, 110223.

Saradara, S. M., Khalfan, M. M. A., Jaya, S. V., Swarnakar, V., Rauf, A., & El Fadel, M. (2024). Advancing building construction: A novel conceptual framework integrating circularity with modified lean project delivery systems. Developments in the Built Environment, 100531.

Alaejos, P., de Juan, M. S., Rueda, J., Drummond, R., & Valero, I. (2012). Quality assurance of recycled aggregates. In Progress of recycling in the built environment: Final report of the RILEM Technical Committee 217-PRE (pp. 229–273). Springer.

Hendriks, C. F. (1994). Certification system for aggregates produced from building waste and demolished buildings. In Studies in Environmental Science (Vol. 60, pp. 821–834). Elsevier.

Jeon, S. M. (2024). Comprehensive review of quality certification follow-up management audit outcomes following the dual role as quality manager for recycled aggregate. Journal of the Korea Institute of Building Construction, 24(2), 239–248.

Bühler, M. M., Michalski, P., Michalski, A., Meyer, S., Birle, E., Roff, R., Lang, C., Schmidt, W., Cudmani, R., Fritz, O., & Baltes, G. (2023). Recyclable and efficient construction using mineral landfill materials and demolition wastes. Preprints, 2023.

Nassiri, S., Harvey, J., & Miller, S. (2025). Lab2Slab2Practice: A framework for a faster implementation of innovative concrete materials and technology.

Van den Heede, P., & De Belie, N. (2012). Environmental impact and life cycle assessment (LCA) of traditional and “green” concretes: Literature review and theoretical calculations. Cement and Concrete Composites, 34(4), 431–442.

Wang, Z., & Wu, B. (2023). A mix design method for self-compacting recycled aggregate concrete targeting slump-flow and compressive strength. Construction and Building Materials, 404, 133309.

Smical, I., Filip-Văcărescu, F., Danku, G., & Paşca, V. (2015). Research on recycling of hardened mortar from construction and demolition waste. Journal of Applied Engineering Sciences, 5(2), 81–86. https://doi.org/10.1515/jaes-2015-0025

Mousa, H. H., Kadhem, A. A., Al-Bahrani, H. S., Jabal, Q. A., & Alasadi, L. (2024). Study the re-use of construction and demolition waste for a friendlier environment: Waste concrete and waste granite aggregates. Civil and Environmental Engineering, 20(2), 711–719. https://doi.org/10.2478/cee-2024-0053

How to Cite This Article

Tokala, S., Lingeshwaran, N., Ponni, M., Ushakranti, J., George Fernandez Raj, A., & Chinnasamy, M. (2026). Recycling Construction and Demolition Waste into Coarse Aggregates: A State-of-the-Art Review. Civil and Environmental Engineering, 0 (0). https://doi.org/10.2478/cee-2026-0059