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Report on Recycled Concrete Aggregate

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Recycled Concrete Aggregate: Production, Recycling, Properties, and Applications



(Photo: Emad Mekay, International Bar Association Middle East Correspondent, May 27, 2021)

The reconstruction of Syria requires cost-effective, resource-efficient, and scalable construction strategies that can be rapidly deployed. Recycled concrete aggregate (RCA), produced from demolition debris, offers a practical solution for converting widespread rubble into a usable construction material. When properly processed, characterized, and specified, RCA can be used in applications ranging from road base and engineered backfill to structural concrete and rigid pavements.

The technical challenge is not whether RCA can be used, but how carefully its variable properties are incorporated into design and construction practice. Compared with natural aggregate, RCA generally exhibits lower density, higher water absorption, greater porosity, and increased variability due to adhered residual mortar and source-dependent quality. These differences directly affect workability, strength, durability, shrinkage, and long-term structural performance.

This report presents a consolidated and publication-ready technical framework covering RCA sources, production processes, material properties, mixture design considerations, structural applications, and performance implications, with specific relevance to post-conflict reconstruction in Syria.

1—Introduction

The widespread destruction of infrastructure across Syria has generated millions of tons of construction and demolition (C&D) waste. Managing this material represents both a major logistical challenge and a significant opportunity for resource recovery. Rather than treating debris as waste, it can be repurposed to support reconstruction efforts.

Recycled concrete aggregate is produced by crushing and processing demolished concrete. With appropriate treatment, grading, and quality control, it can partially or fully replace natural aggregates in a variety of construction applications.

In post-conflict environments, where supply chains are disrupted and construction demand is exceptionally high, RCA provides locally available material that reduces dependence on imported aggregates, lowers transportation costs, and accelerate rebuilding. Its use also supports sustainable construction practices by reducing reliance on virgin aggregate extraction and minimizing waste disposal.

This report presents a technical overview of RCA, including its sources, production processes, material properties, mixture design considerations, and applications in reconstruction.

2—Sources and generation of RCA



(*Homs, Syria's third-largest city, shattered by war. Photo: The Arab Weekly—Khalil Hamlo*)

Syria is actively transforming the widespread destruction of its built environment into a vital resource, converting the rubble from more than 130,000 destroyed buildings into a key sustainable solution for nationwide rebuilding. With approximately 70% of these ruined structures constructed from reinforced concrete, the resulting debris provides a massive, readily available source for producing RCA (Rashwani et al. 2023). By repurposing this waste into new concrete, the strategy directly links post-war recovery to a circular economy, creating a cost-effective, sustainable pathway to rebuild essential infrastructure while reducing the demand for new, raw materials. An efficient and reliable RCA supply chain depends on a clear understanding of concrete waste availability, sources, and collection processes.

2.1—Sources of concrete waste

Recycled concrete aggregate is produced from construction and demolition (C&D) waste, primarily originating from:

(a) **Demolished/destroyed structures**, including buildings, bridges, and foundations

(b) **Transportation infrastructure**, including roads, pavements, and airport facilities, which typically produce more uniform material requiring less intensive processing

In Syria, a significant portion of the debris generated by the 14-year civil war consists of reinforced concrete, providing a substantial and locally available source of material for RCA production. This material can be directly integrated into reconstruction activities, reducing the need for imported materials and minimizing transportation requirements.

2.2—Collection and transportation

Efficient collection and transportation systems are essential for producing usable RCA. The process begins with on-site segregation, where concrete debris is separated from materials such as wood, plastics, metals, and hazardous waste. In post-conflict Syria, this step presents significant challenges, including highly mixed debris compositions, restricted site access due to unexploded ordnances, limited availability of specialized equipment, and persistent worker safety risks from unstable structures and dust exposure. Nevertheless, implementing even basic sorting protocols at the source significantly enhances RCA purity, reduces subsequent processing demands, and improves overall recycling efficiency.

Following segregation, concrete waste is either transported to processing facilities or crushed on-site using mobile crushing units near demolition sites. Mobile systems are particularly advantageous in damaged urban areas, as they:

(a) Reduce hauling distances and associated costs

(b) Enable rapid processing and reuse

(c) Support decentralized reconstruction efforts

Strategic placement of processing facilities and careful planning of transport routes are critical for maintaining efficiency, particularly where infrastructure and fuel availability are constrained.

2.3—Volume and availability trends

The large volume of concrete waste in Syria, resulting from widespread destruction of urban infrastructure, presents a prospect for the construction sector. In the early phases of reconstruction, the supply of raw material for RCA production is expected to exceed immediate demand, creating an opportunity to establish large-scale recycling operations and stockpile processed aggregates. With organized collection, efficient transportation, and strategic planning, RCA can turn rubble into a real asset for reconstruction. This approach accelerates the rebuilding process faster while making it more cost-effective and affordable.

Over time, as reconstruction progresses and debris is gradually cleared, the availability of concrete waste may decline. However, ongoing infrastructure rehabilitation and urban redevelopment will continue to generate a steady, though smaller, supply of recyclable material. This trend highlights the importance of early investment in RCA processing capacity and the development of long-term strategies for sustainable material management.

3. Production process of RCA



(Recycled concrete aggregate processing site—Source Mineral Newsletter issue 05/2023)

Producing usable RCA from demolished concrete requires more than simply crushing old concrete. It is a carefully managed process that begins with selective demolition and ends with a clean, well-graded aggregate suitable for its intended engineering applications. In post-conflict Syria, where speed, cost, and resource efficiency are critical, establishing a clear and practical production process is essential.

The choice of processing setup matters. On-site mobile crushers cut transport costs and work well for road base and fill. Off-site permanent plants produce higher-quality RCA suitable for structural concrete but require hauling debris to a central location. Between these extremes, on-site stationary plants offer a middle ground with better control than mobile units and lower transport costs than off-site facilities.

Quality control is not optional. Regular testing of gradation, density, water absorption, and contaminants is essential—especially in resource-constrained environments where variability is high. Even basic testing protocols significantly improve confidence in RCA and expand its range of safe applications.

In short, the journey from demolished building to usable aggregate depends on three things: choosing the right crushing setup, removing contaminants effectively, and verifying quality at every stage.

3.1—Crushing and processing stages

Demolished concrete arrives typically in large pieces, which are first reduced to manageable sizes before undergoing further crushing and grading, see Fig. 3.1. This step ensures that the material can be efficiently processed into aggregates suitable for construction use.



Fig. 3.1—Transformation of large concrete sections to usable recycled concrete aggregate (*Source: Grinder crusher screen website: https://www.grindercrusherscreen.com/blog/20904-concrete-recycling-the-key-to-increasing-profitability*)

3.1.1 *Overview of RCA production approaches*

RCA can be produced using different operational setups, depending on project scale, location, and quality requirements:

(a) On-site mobile processing: Portable crushers are deployed directly at demolition sites, which cuts transportation costs and is ideal for producing lower-grade applications for base or fill materials

(b) On-site stationary processing: Temporary fixed plants offer better control and higher output than mobile units

(c) Off-site permanent facilities: Centralized recycling plants, typically located in urban areas, produce consistent and higher-quality RCA suitable for structural concrete and more demanding applications

3.1.1.1 *On-site crushing*

Crushing concrete at the construction site using portable crushers is often more economical and eco-friendlier than hauling material to quarries.

(a) Large road-portable plants process up to 600 tons per hour, typically including a side discharge conveyor, screens, and a return conveyor to re-crush oversized chunks

(b) Compact units manage up to 150 tons per hour in confined spaces

(c) Crusher attachments on construction equipment such as excavators can process up to 100 tons per hour, making small-scale crushing practical and economical, Fig. 3.1.1



Fig. 3.1.1—Crusher bucket for excavator (Source: forconstructionpros.com)

3.1.2 Initial stages: Demolition, collection, and pre-processing

The process starts with selective demolition to isolate concrete from asphalt, wood, plastics, soil, and other debris. Reinforcing steel is cut or removed pre-crushing to boost efficiency. Multi-stage crushing achieves target sizes and quality:

(a) Primary crushing: Jaw or impact crushers reduce over 600 mm to 75-300 mm, freeing embedded steel bars, making them easier to remove later. The jaw crusher compresses concrete between a fixed and a moving plate, breaking it into smaller fragments while producing relatively few fine particles, see Fig. 3.1.2a.

(b) **Secondary and tertiary crushing:** After primary reduction, the material is then passed through a secondary crusher to achieve the desired aggregate size. This stage produces a more uniform and refined product, suitable for construction applications such as road base, subbase, or concrete production. Depending on requirements, additional crushing stages may be used to further improve particle shape and size distribution.

- **Impact crushers:** Impact crushers operate using spinning rotors with attached bars that fling concrete against solid plates or rods, breaking it into smaller pieces. These crushers can be portable, mobile, or stationary, depending on the project requirements, see Fig. 3.1.2b.
- **Cone crushers:** Used for secondary or tertiary crushing. Concrete is compressed between two cone shaped plates producing well-graded aggregates suitable for higher-quality applications of 40 mm or less, see Fig. 3.1.2c.

Crusher type plays a critical role in determining the final properties of RCA. It affects RCA particle shape, which influences concrete workability (Etxeberria et al. 2007). Natural aggregates are generally angular with smooth surfaces. RCA, by contrast, often becomes more rounded and spherical during processing, which can improve workability (Sagoe-Crentsil et al. 2001). This rounding is partly due to residual mortar smoothing the sharp edges of the original aggregate, allowing new mortar to flow more easily around the particles. Table 3.1.2 summarizes the different crusher types.

Table 3.1.2—Crusher types and characteristics

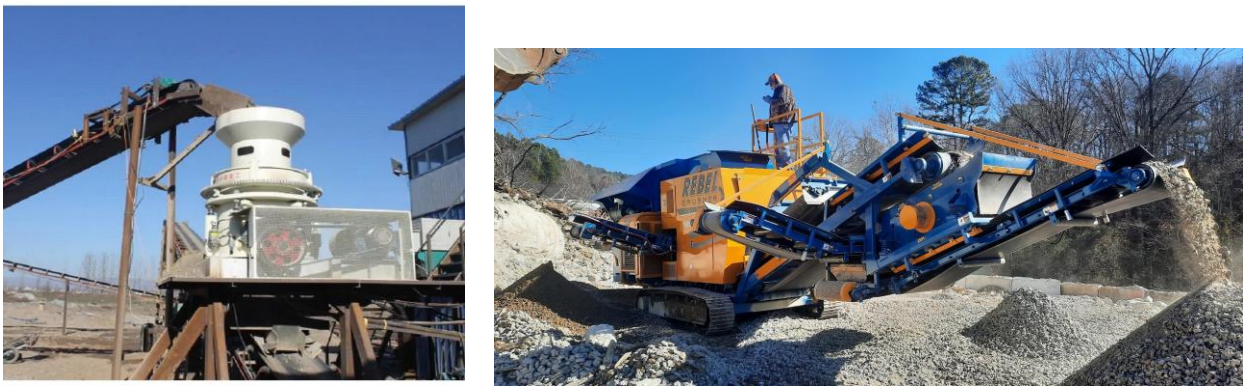
Crusher type	Fedd size (approx.)	Material processed	Output characteristics	Typical use
Jaw Crusher	600 mm or more	Large concrete sections	Fewer fines, larger aggregate	Primary crushing; base/fill RCA
Impact Crusher	≤ 300 mm	Concrete and mortar	Produces more fines, smaller aggregates	Secondary crushing; finer gradation
Cone Crusher	Variable	Coarse or secondary material	Well-graded aggregates	Secondary/tertiary crushing; structural RCA

Project staging can also affect RCA availability. To ensure that sufficient material is available when needed, equipment production rates and project sequence should be carefully coordinated. If on-site RCA production cannot meet demand, virgin aggregates may be used as a supplement (Fick, 2017 and Snyder et al. 2018).



(a) (b)

Fig. 3.1.2a—Jaw crusher; (a) stationary, (b) portable



(a) (b)

Fig. 3.1.2b—Impact crusher; (a) stationary, (b) portable

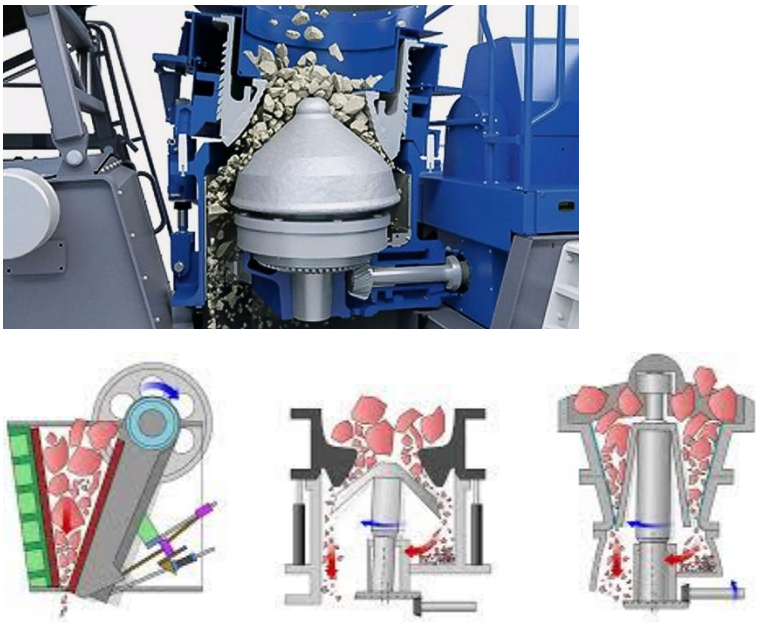


Fig. 3.1.2c—Cone crusher

3.2—Screens and grading

In addition to crushers, RCA processing typically requires screens, conveyors, and equipment for stockpile management. Screening machines come in various configurations. They contain one or more heavy-duty metal decks fitted with steel wirecloth arranged in a grid pattern. The woven wires create uniform openings depending on the desired aggregate size. Vibration shakes the screen, causing smaller particles to fall through while larger material moves across and off the deck (see Fig. 3.2). Regarding gradation, standards for structural concrete define acceptable ranges, and RCA gradation typically falls within these specifications, indicating that RCA can meet standard requirements without additional adjustments (Sagoe-Crentsil et al. 2001; Shayan and Xu 2003).

RCA stockpiles should be kept clean and free of contaminants such as organic material, soil, or other construction debris. Proper management also helps prevent environmental issues such as high-pH runoff during rain (Cavalline, 2018).



Fig. 3.2—Double deck vibrating screen (*Source: https://eaglecrusher.com/what-are-screens-and-what-can-they-do-for-you/*)

3.3—Contaminant removal and cleaning

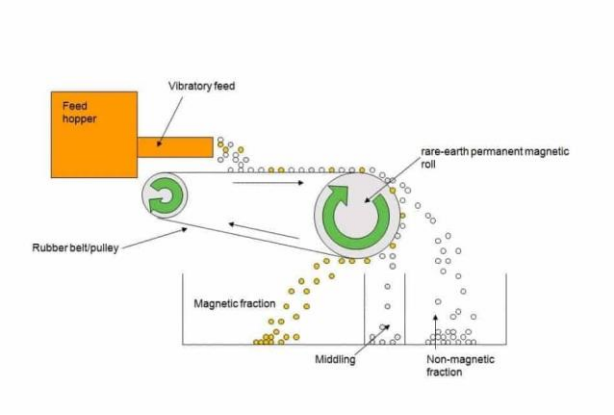
One of the most critical steps in RCA production is the removal of unwanted materials that may compromise performance. Common separation methods include:

(a) Magnetic separation: Removes reinforcing steel and other ferrous metals. This not only improves aggregate quality but also allows for recycling of steel, Fig. 3.3a(a)

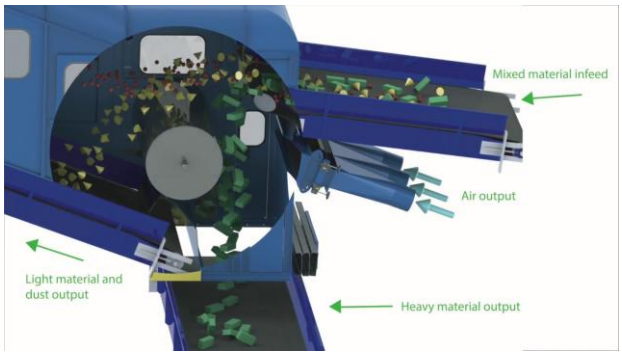
(b) Air separation: Eliminates lightweight materials such as plastics and paper, Fig. 3.3a(b)

(c) Manual sorting: Used for removing visible debris, for example, wood, plastics, paper, and other lightweight materials through manual picking or air separation systems, Fig. 3.3a(c)

(d) Washing: Screening, washing, or selective demolition practices help reduce the presence of asphalt residues and fine contaminants such as soil and clay, Fig. 3.3a(d)



(a)



(b)



(c)



(d)

Fig. 3.3a—Different separation methods; (a) Schema of a magnetic separator (Source: Bunting-Redditch®); (b) Air drum separator (Source: Impact air systems); (c) Manual rubble sorting in Iraq, including the removal of non-recyclable waste, such as plastic materials, furniture, and others. (Source: Al and Al-Tameemi 2021); (d) Washing crushed concrete aggregate (Source: McLanahan)

Figure 3.2b shows a flow diagram for a typical second-generation plant capable to remove contaminants like plastic, wood, and metal from debris. It utilizes advanced automated sorting and multi-stage crushing to produce higher-purity aggregate compared to the manual or basic mechanical methods of first-generation plants.

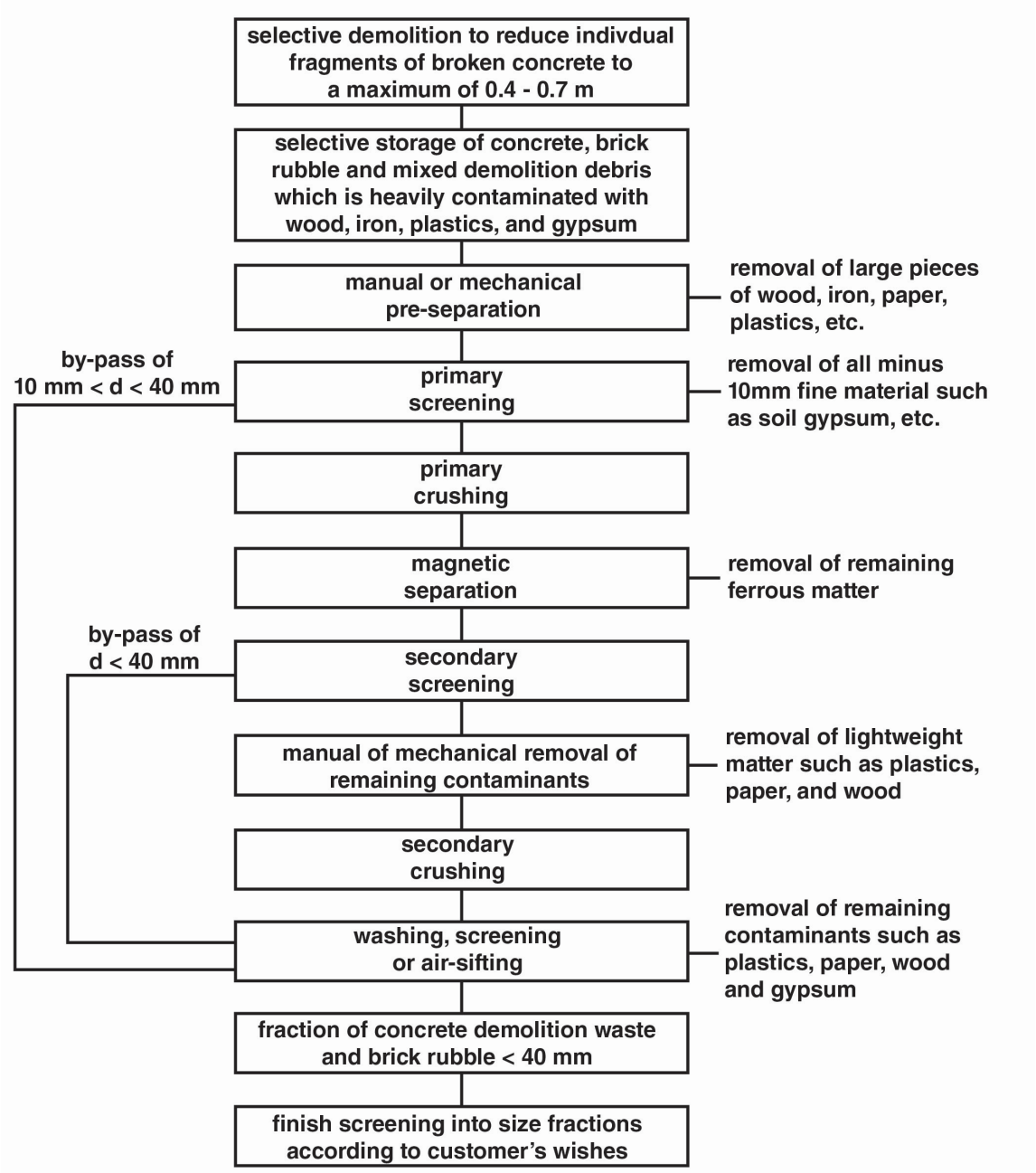


Fig. 3.3b—Processing procedure for building and demolition waste (*Source: ACI-PRC 555*).

3.4—Quality control procedures

Consistent quality control is essential to ensure that RCA meets engineering standards and performs reliably in construction applications. Key procedures include:

(a) **Material inspection:** Regular visual and laboratory checks to assess cleanliness, particle shape, and composition

(b) **Gradation testing:** Ensuring that aggregate size distribution meets project specifications

(c) **Physical and mechanical testing:** Evaluating properties such as compressive strength, density, water absorption, and abrasion resistance

(d) **Moisture control:** Monitoring and adjusting moisture levels to maintain consistent performance during mixing and placement

Establishing simple, standardized testing protocols is particularly important in resource-constrained environments. Even basic quality control measures can significantly improve confidence in RCA and expand its range of applications.

4—Material properties of recycled concrete aggregate



(Source: Water-Washed Fine and Coarse RCA for Real Scale Concrete Production in Barcelona, Etxeberria et al. 2022)

The main difference between recycled concrete aggregate and natural aggregate is the old mortar adhered to the original aggregate. This porous, less dense mortar affects nearly every property of the aggregate and the concrete made from it.

RCA physical properties exhibit lower density and higher water absorption and porosity, which affect mixture proportioning, workability, and durability, requiring appropriate adjustments during design and production. Mechanically, RCA concrete may show reductions in compressive strength, stiffness, and abrasion resistance, particularly at high replacement levels. However, these effects are strongly dependent on the quality of the source material, processing methods, and mixture design.

Despite these differences, RCA is suitable for engineering applications when properly characterized and incorporated through performance-based mixture design. It can deliver reliable and predictable performance across a wide range of uses, including structural and non-structural applications. RCA represents a viable and practical material for construction, particularly in resource-constrained or large-scale reconstruction contexts, where its benefits in availability, cost, and sustainability are substantial.

4.1—Physical Properties

The physical properties of aggregates, such as density, water absorption, and porosity, determine their suitability for various applications and significantly affect concrete mixture performance, including workability, durability, and long-term behavior, which is discussed in detail in Chapter 5. With RCA, the properties differ from natural aggregates due to the residual cement mortar adhering to particle surfaces after crushing. (Akbulut et a. 2025).

4.1.1 *Density*

Density is perhaps the most immediate obvious difference between RCA and natural aggregate. Natural aggregates, such as granite, limestone, basalt typically show bulk densities in the range of 1,500 to 1,700 kg/m³ and particle densities around 2,600 to 2,800 kg/m³. RCA, however, has lower values, ranging between 1,200 and 1,500 kg/m³ in bulk density and between 2,100 to 2,500 kg/m³ in particle density (Shayan and Xu 2003 and Sagoe-Crentsil et al. 2001). This reduction is primarily due to the lower-density of residual cement mortar attached to the original aggregate particles.

This attached mortar is inherently less dense than natural rock because it is a porous, heterogeneous matrix of hydrated cement, sand, and voids. When concrete is crushed, the aggregate particles that result are coated in this mortar. In many cases, the mortar makes up a significant fraction of the particle's mass.

The higher the mortar content, the lower the density of the RCA, This reduced density has several implications:

(a) Reduced concrete self-weight, which may be advantageous in certain structural applications

(b) Altered mixture proportioning, requiring adjustments in volume-based calculations

(c) Potential effects on mechanical strength of concrete

The lower density of RCA translates into a lower unit weight for the RCA concrete. Several factors influence the magnitude of this unit weight reduction, including:

(a) Type of RCA used (coarse vs. fine)

(b) Percentage of natural aggregate replacement

(c) Specific gravities of the source concrete components

(d) Mortar fraction content of the RCA

In practice, RCA concrete shows 10–15% lower unit weight than conventional mixtures (Hansen & Narud 1983 and Hansen 1986). This reduction must be accounted for in structural calculations whenever self-weight is a significant design parameter.

4.1.2 *Water absorption*

RCA has two notable characteristics: high water absorption and low specific gravity (Verian et al. 2018). Absorption typically ranges from 3% to 10% or more, compared to just 0.5% to 4% for natural aggregates (Building Contractors Society of Japan, 1978; Hansen 1986; ACI E7-01). This difference comes from the porous mortar still attached to the RCA particles, and it creates problems starting at the mixing stage.

Higher absorption drives up water demand. If left unaddressed, it reduces workability. The usual fixes are pre-soaking the aggregate or adjusting the mix water. When dry RCA is used without these adjustments, it absorbs water from the paste. That lowers the effective water-to-cement ratio, resulting in a stiff, hard-to-work mix. On the other hand, adding extra water without redesigning the mix leads to weaker, more permeable concrete.

4.1.3 *Porosity*

Porosity and water absorption are closely related aggregate properties and are both significantly influenced by the presence of residual mortar. As a result, RCA is inherently more porous than natural aggregate. The adhered mortar contains capillary pores and microcracks that developed during the original concrete service life and are often exacerbated during demolition. In addition, the crushing process can introduce further microcracking within both the mortar and, in some cases, the original aggregate particles.

The increased porosity leads to higher permeability in concrete, which can reduce resistance to freezing-and-thawing cycles and compromises durability in aggressive environments by facilitating the ingress of water and deleterious ions such as chlorides and sulfates (Hu et al. 2022). At the same time, the higher absorption capacity of RCA can provide a beneficial internal curing effect. Water retained within the aggregate particles may be gradually released during hydration, which can enhance cement hydration and improve performance in low water-cement mixtures. Table 4.1.3 summarizes the key material properties of RCA in comparison to natural aggregate.

Table 4.1.3—Key properties of recycled concrete aggregate (RCA)

Property	RCA value/range	Natural aggregate	Notes to RCA
Density (kg/m³)	2,100 – 2,500	2,600 – 2,800	Lower due to residual mortar
Water Absorption (%)	3 – >10	0.5 – 4.0	Higher due to porous adhered mortar
Porosity (%)	Higher than NA*	Lower	Affects mixture design and workability
Shape & Texture	Angular, rough	Rounded or sub-angular	Improves compaction but may reduce workability
pH	>11	7 – 9	Higher alkalinity increases risk of alkali reactions

* NA – natural aggregate

4.2—Mechanical properties

The mechanical properties of RCA directly influence the strength and durability of concrete. While RCA can perform adequately in many applications, its characteristics differ from those of natural aggregates. Two properties in particular, compressive strength and abrasion resistance, are key to the success of most structural and pavement applications.

4.2.1 *Compressive strength*

Concrete made with RCA generally exhibits lower compressive strength compared to concrete made with natural aggregates, particularly at high aggregate replacement levels (Xiao et al 2005). The reduction is typically in the range of 5% to 24% and depends on several key factors:

(a) Quality of the original concrete: Higher-strength source concrete produces denser and less porous RCA with fewer micro-cracks, which helps limit strength loss in the new mixture (Hu et al. 2022)

(b) Degree of mortar adherence: The amount and condition of adhered mortar also play a significant role; residual mortar that is weak or porous introduces microcracking and reduces overall strength (Tam et a. 2005; Etxebrria et al. 2007)

(c) RCA replacement level: Higher replacement levels generally leads to greater reductions in compressive strength (Adams and Jayasuriya 2019; Lu 2024)

(d) Water-to-cement ratio: Strength decreases with increasing w/c ratio, similar to conventional concrete (Hansen and Narud 1983)

In conventional concrete, there is one ITZ; the boundary between the aggregate particle and the surrounding cement paste. In RCA concrete, there are effectively two; the original boundary between the natural aggregate and the old mortar, and a new boundary between the old mortar and the new cement paste, see Fig. 4.2.1a. Therefore, the weaker ITZ between the RCA and new cement paste contributes to the compressive strength reduction (Adams and Jayasuriya 2019; Zheng et al. 2021).

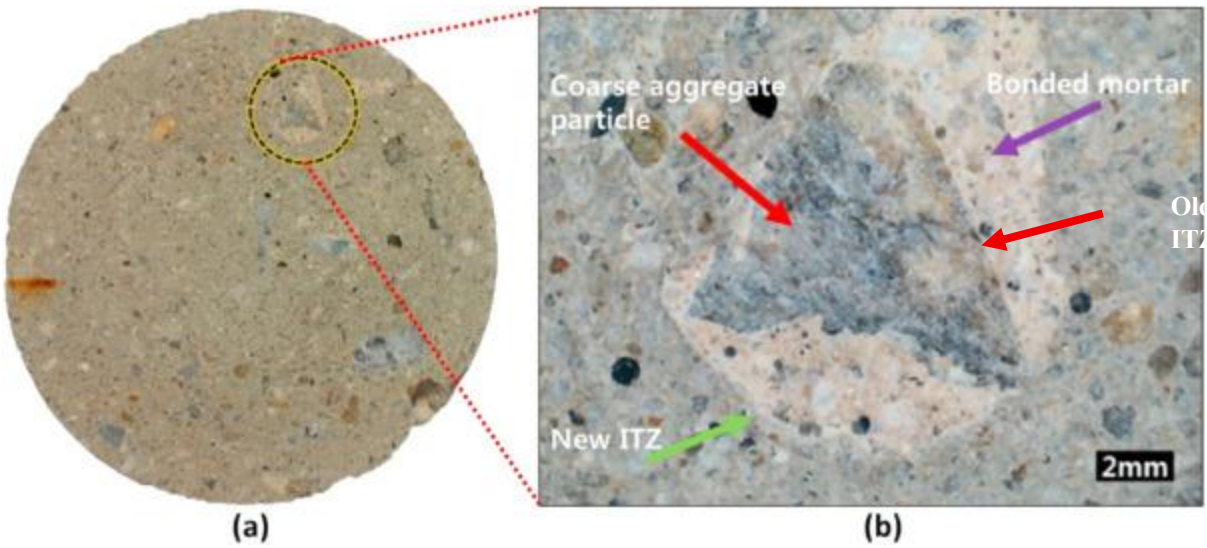


Fig. 4.2.1a—(a) Surface of RAC, (b) RCA, bonding mortar and old and new ITZ (in RAC) (Source: Zheng et al.).

Several strategies can be used to mitigate strength reductions and improve the performance of concrete containing RCA:

(a) Use of supplementary cementitious materials (SCMs), for example, fly ash, slag, silica fume, can enhance matrix density and bonding (Wang et al. 2023)

(b) Optimize RCA gradation and particle packing improves overall compactness and reduces voids (Adams and Jayasuriya 2019, Hu et al. 2022)

(c) Pre-treatment of RCA that remove or strengthen adhered mortar can further improve aggregate quality (Peiris et al. 2025)

(d) Partial RCA replacement, limiting RCA replacement to moderate levels—typically 30% to 50%—often results in relatively small strength reductions, on the order of 5% to 15% (Limbachiya et al.2000; Silva et al. 2014)

The percentage of natural aggregate replaced by RCA significantly influences concrete performance, Limbachiya et al. (2000):

(a) Low replacement levels (≤ 30%) typically result in minimal performance loss

(b) Moderate levels (30–70%) require careful mixture design adjustments

(c) High levels (> 70%) may significantly affect strength and durability unless enhanced processing or treatment is used

Fig. 4.2.1b shows that mixtures with about 30% RCA replacement closely match the compressive strength of conventional concrete, whereas mixtures with 100% RCA replacement, exhibit noticeably lower strength, particularly at low water-to-cement ratios.

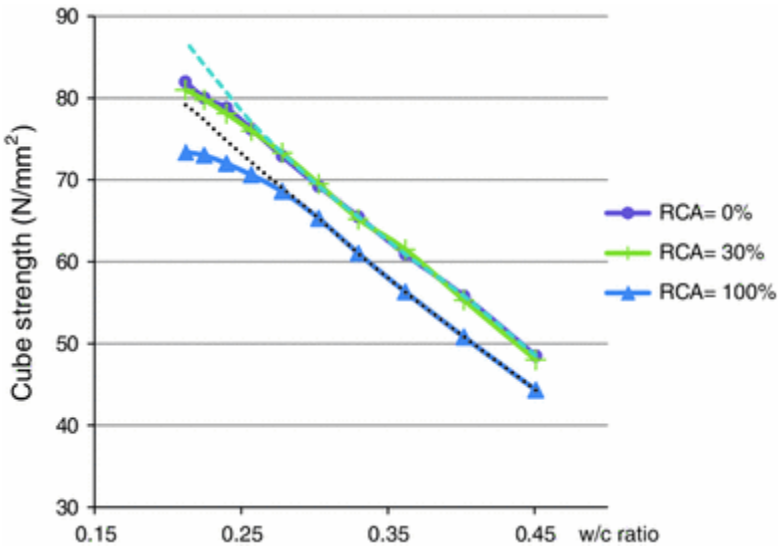


Fig. 4.2.1b—Concrete compressive strength versus water-to-cement ratio for RCA contents of 0–100 % (Source: Limbachiya et al. 2000).

Despite these limitations, RCA can meet required strength criteria in many practical applications, including road bases, non-structural concrete, and structural elements when appropriate design measures are implemented.

4.2.2 *Splitting tensile strength*

The average splitting tensile strength of RAC varies with the RCA replacement level. Overall, as the replacement level increases, the tensile strength steadily decreases, see Fig. 4.2.2 (Yangn et al. 2008a). This drop in strength is mainly due to the weak bonding between the different material phases in the concrete, particularly the new and old ITZ, when subjected to indirect tensile stresses (Yan et al. 2024).

Under splitting tensile loads, the interface between the old adhered mortar and the fresh cement paste becomes a critical weak point. Unlike compressive stresses, which can be transferred through the stronger aggregate cores, tensile stresses concentrate along these interfacial boundaries. As the RCA content increases, so does the total surface area of these weak zones, leading to a reduction in the material's ability to resist cracking.

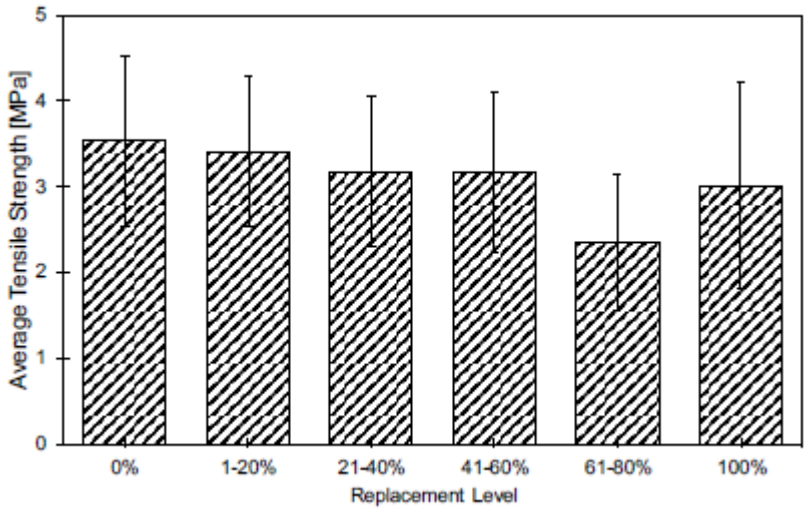


Fig. 4.2.2—*Mean splitting tensile strength variation of RAC systems over RCA replacement levels* (*Source: Adams and Jayasuriya*)

4.2.3 *Flexural strength*

Recycled concrete aggregate generally has slightly lower flexural strength than conventional concrete. However, as shown in Figure 4.2.3, the highest average flexural strength is typically observed at RCA replacement levels between 1% and 20%. Overall, an approximate 10% reduction in 28-day strength has been reported, mainly due to microcracks and weaker zones within the RCA that form during the demolition process (Maruyama 2004; Sato et al. 2007; Fathifazl et al. 2009; Kang et al. 2012).

The increase in flexural strength at low replacement levels (1–20%) is largely attributed to improved bonding between the RCA and the new cement matrix. The rough, angular texture of RCA particles increases the surface area available for mechanical interlock, which enhances adhesion with the surrounding cement paste. Consequently, when mixtures are properly proportioned, RCA concrete beams can achieve flexural performance comparable to natural aggregate concrete at both serviceability and ultimate limit states. In such cases, existing code provisions generally remain applicable without modification (Fathifazl et al., 2009).

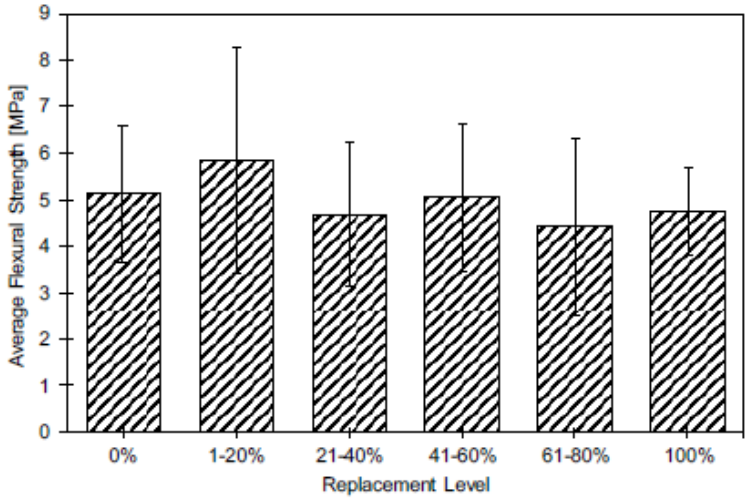


Fig. 4.2.3—*Mean elastic modulus variation of RAC systems over RCA replacement levels (Source: Adams and Jayasuriya*)

4.2.4 *Bond strength*

In reinforced concrete members, sufficient bond strength between concrete and reinforcing steel is essential. Studies on the bond behavior of RCA concrete with steel are limited, but research indicates that bond strength is generally comparable to conventional concrete, or slightly lower. Choi and Kang (2008) found no significant difference, while Butler et al. (2011) reported a reduction of about 9 to 19% even with 100% coarse RCA, which is considered negligible for most applications.

4.2.5 *Modulus of elasticity and Poisson's ratio*

The modulus of elasticity of RCA concrete is typically lower than that of conventional concrete because the adhered mortar in RCA is less stiff than natural aggregates (Xiao et al. 2012a). The amount and quality of adhered mortar depend on the type of crusher, particle size, and the RCA replacement level (ACPA 2009). A 10% decrease in modulus of elasticity was recorded at 50% RCA replacement (Bekoe et al., 2010) , while 35% decrease at 100% RCA replacement was recorded (Limbachiya et al. 2012). Other

studies in Japan—Building Contractors Society, 1978—found reductions of 10–33% for coarse RCA, and 25–40% when both fine and coarse RCA were used (ACPA 2009 and FHWA 2022).

Poisson's ratio, however, shows minimal change. Values for RCA concrete range from 0.15 to 0.23 (Sofi et al. 2012), and studies by Verian et al. (2013) found no clear correlation between RCA replacement and Poisson's ratio.

4.2.5 *Abrasion resistance*

Abrasion resistance is important in applications where aggregate is exposed to surface wear, such as road pavements, industrial floors, and some structural slabs. It is commonly evaluated using the Los Angeles abrasion (LA) test. Natural aggregates with good abrasion resistance typically show LA values below 25%. RCA generally records higher losses, often in the range of 30% to 50%, indicating lower resistance to abrasion (Sagoe-Crentsil et al. 2001; Shayan and Xu 2003; Tavakoli and Soroushian 1996). This behavior is expected, because RCA has residual mortar that can detach easily at the ITZ, refer to Section 4.2.1. RCA also shows increased wear under mechanical loading.

The mortar attached to RCA particles is softer and more friable than the parent rock. Under repeated impact and friction, it tends to break away more readily, leading to higher material loss. For road sub-base applications, where particles are not directly exposed, this may be acceptable as it poses a significant limitation for high-traffic floors or wearing courses. In such cases, careful material specification or blending with natural aggregates is often recommended. RCA particles are typically more angular and rougher, though residual mortar can smooth sharp edges and improve workability (Etxeberria et al. 2007).

4.3—Comparison with Natural Aggregates

Natural aggregates generally outperform RCA in terms of density, strength contribution, abrasion resistance, and consistency, particularly in high-performance structural concrete and pavements exposed to severe service conditions (Hansen 1986, Limbachiya et al. 2000). In such applications, 100% RCA replacement may be impractical because of the aggregate's higher porosity, greater water absorption, residual mortar, and ITZ (Silva et al. 2014). For this reason, partial replacement or mechanical/chemical treatment of RCA is often preferred to preserve required structural and durability performance (ACPA 2009, Tam et al. 2005; Etxeberria et al. 2007).

Comparative properties

(a) Natural aggregates typically have higher density, lower absorption, lower porosity, and more predictable quality (Silva et al. 2014)

(b) RCA typically has lower density, higher absorption, higher porosity, and greater variability because of adhered mortar and microcracking (Hansen 1986)

(c) In practice, the performance gap narrows when RCA is processed, treated, or used at moderate replacement levels (ACPA 2009)

4.4—Variability and influencing factors

One of the most significant challenges in using RCA is its variability. Unlike natural aggregates, which are typically sourced from controlled quarry operations, RCA properties stem from diverse demolition sources and depend on multiple hard-to-control factors.

4.4.1 *Source of original concrete*

The original concrete mixture is the most fundamental variable affecting RCA performance, exerting the strongest influence of any single factor. Key variables include:

(a) Original mixture design

(b) Strength class

(c) Type of cement and aggregates used

(d) Age and exposure conditions

Concrete from high-strength structures generally produces higher-quality RCA than that from low-strength or deteriorated structures.

4.4.2 *Processing methods*

The crushing process itself matters. Jaw crushers, impact crushers, cone crushers affect the particle shapes, surface textures, and adhered of mortar content, see Chapter 3. Aggressive crushing can break off more mortar that would otherwise remain attached potentially improving RCA density and reducing absorption characteristics. However, it also produces more fines and can introduce additional micro-cracking. The balance between mortar liberation and particle damage is essential in processing plant design.

4.4.3 *Contaminants*

Demolished concrete often contains brick, tile, plasterboard, timber fragments, glass, and occasionally hazardous materials such as asbestos or tar. The presence of even small quantities of gypsum-rich plaster or sulfate-bearing materials can have serious consequences for concrete durability, as sulfate attack can cause expansion and cracking of the paste (Lee et al 2005). Effective sorting and quality control at the recycling facility is therefore essential, but it adds cost and is not universally implemented.

Age and weathering of the source concrete can also influence RCA properties. Older concrete has typically undergone greater carbonation of the cement paste, which actually densifies the mortar and can reduce its porosity relative to young paste. However, older concrete may also have more pre-existing cracking and more inconsistent quality due to the less controlled mixing practices of earlier eras.

4.5—Conclusion

RCA's variability demands a fundamentally different approach than quarried aggregates. Robust quality assurance, including regular testing of bulk density, water absorption, and contaminant levels, is not optional; it is essential for any responsible specification. Standards such as EN 12620 7and ASTM C33 provide frameworks for aggregate classification. They were developed primarily for natural aggregates and require careful adaptation for RCA.

Its properties are inferior to natural aggregates in density, absorption, and consistency, but these differences can be addressed through rigorous characterization, mixture design adjustments, and conservative structural specifications. RCA is rarely unsuitable; the key question is how thoughtfully it is applied.

5—Concrete mixture design with recycled concrete aggregate



(Source: https://doi.org/10.1590/1517-7076-RMAT-2023-0382)

Recycled concrete aggregate is a viable but non-equivalent substitute for natural aggregate, requiring careful mixture design adjustments. Its higher absorption and variability make material characterization and water management essential to control workability and maintain the intended water-to-cement ratio.

Concrete mixture with RCA typically exhibits reduced workability, faster setting, and lower strength, along with higher permeability, shrinkage, and creep, refer to Chapter 4. These effects are effectively mitigated using lower water-to-cement ratios, supplementary cementitious materials, and appropriate admixtures.

Reliable performance depends on batch-specific testing and trial validation. When properly designed and controlled, RCA concrete can meet structural and durability requirements while contributing to sustainability goals.

5.1—Introduction

Designing a concrete mixture involves balancing multiple, often competing objectives, such as meeting a specified compressive strength, ensuring sufficient workability for placement and consolidation, achieving the necessary durability for the given exposure conditions, and doing so within increasingly stringent sustainability constraints (ACPA 2009, FHWA 2022). These objectives become more difficult to manage because RCA differs from natural aggregate, refer to Chapter 4.

The main challenge with RCA is not that it is unsuitable for concrete. Rather, it behaves differently from natural aggregate, which is the basis for most conventional mixture design procedures. As detailed in Chapter 4, RCA differs from natural aggregate in several key respects, including higher water absorption and porosity, lower density, rougher surface texture, and the presence of residual mortar (Verian et al. 2018; Hansen 1986). These characteristics often act together, reducing workability, increasing water demand, and making both fresh and hardened properties more inconsistent (Cavalline et al. 2022).

RCA can be used successfully, but it cannot simply be substituted for natural aggregate without adjusting the mixture design (Adams and Jayasuriya. 2019). Effective use requires understanding how RCA affects the concrete system and making deliberate changes at each stage of design, from aggregate characterization through fresh properties to hardened performance and durability (Xiao et al. 2012a).

5.2—Characterizing the aggregate before you start

Any mixture design process begins with a clear understanding of the materials, and this is especially critical when using RCA. Unlike natural aggregates sourced from consistent geological deposits, RCA variability (see Section 4.4) requires mixture designs to be based on project-specific material characterization.

The three physical properties that matter most for mixture design are density, water absorption, and particle shape—refer to Chapter 4. Density affects mixture proportioning and unit weight calculations. Water absorption governs how much free water is available to the paste, directly affecting the effective water-to-cement ratio during mixing. Particle shape affects workability and the volume of paste required to adequately coat aggregate surfaces (McNeil and Kang 2013).

Given the variability in density and mortar content of RCA, standardized acceptance criteria are necessary to ensure reliable performance. International guidelines (see Table 5.2) generally converge on similar thresholds: for most structural applications, RCA should exhibit a density above 2,000 kg/m³ and water absorption below 10%. Some regions adopt stricter limits. For instance, Japan's Class H specification requires densities exceeding 2,500 kg/m³ and water absorption below 3%, closely aligning with natural aggregate performance, while Spain limits absorption to 5%, consistent with widely accepted recommendations for structural concrete (Etxeberria et al., 2007).

Table 5.2: International acceptance criteria for RCA (Source: McNeil & Kang)

Country / Standard	RCA Type / Class	Min. Density (kg/m³)	Max. Absorption (%)
Australia (AS 1996)	Class 1A	≥ 2,100	≤ 6
Australia (AS 1996)	Class 1B	≥ 1,800	≤ 8
Germany (DIN 4226-100)	Type 1	≥ 2,000	≤ 10
Germany (DIN 4226-100)	Type 2	≥ 2,000	≤ 15
Hong Kong (Works Bureau)	–	≥ 2,000	≤ 10
Japan (JIS)	Coarse – Class H	≥ 2,500	≤ 3
Japan (JIS)	Coarse – Class M	≥ 2,300	≤ 5
Japan (JIS)	Coarse – Class L	No limit	≤ 7
Korea (KS F 2573)	Coarse	≥ 2,500	≤ 3
RILEM (1994)	Type 2	≥ 2,000	≤ 10
Spain (EHE 2000)	–	≥ 2,000	≤ 5

The variability inherent in RCA emphasizes the need for verification testing. Absorption can differ significantly between batches, even from the same supplier. A material meeting a 5% absorption limit from one supplier may not meet it from another. Therefore, routine lot testing is essential—not merely procedural—to ensure consistent mixture performance and structural reliability.

5.3—Influence of RCA on concrete mixture

Concrete made with RCA can generally be batched, mixed, transported, and placed using the same methods as conventional concrete. However, differences in the properties of RCA compared to natural aggregates can affect certain fresh concrete characteristics (Cavalline et al. 2022) and accordingly some adjustments are warranted.

Of all the adjustments required when designing with RCA, water management is the most important and often the most overlooked. Because RCA has higher absorption than natural aggregate, dry or partially dry material can draw water from the paste, reducing workability and altering the effective water-to-cementitious ratio during mixing.

Research shows that this effect is measurable. When only coarse RCA is used, about 5% additional water is typically needed to match the workability of a conventional mixture (Mukai et al. 1979). When both coarse and fine RCA are used, the additional water demand can increase to 10–15% (Buck 1973). Fine RCA usually has a greater impact because its smaller particles provide more surface area and carry more adhered mortar, which increases absorption and water demand. For that reason, many sources recommend limiting fine RCA to no more than 30% of the total fine aggregate (Evangelista et al. 2007; ACPA 2009). The effects of fine and coarse RCA on concrete mixture design are presented in Table 5.3.

Table 5.3b—RCA performance in concrete paving: Effects on hardened properties and mitigation strategies (Source: ACPA 2009)

Property	RCA used as Coarse Aggregate	RCA used as Coarse and fine aggregate	Potential adjustments
Compressive strength	0% to 24% less	15% to 40% less	Reduce w/cm ration
Tensile strength	0% to 10% less	10% to 20% less	Reduce w/cm ration
Strength variation	Slightly greater	Slightly greater	Increase average strength compared to specified strength
Modulus of elasticity	10% to 33% less	25% to 40% less	This may be considered a benefit with regard to cracking of slabs-on-ground
Specific gravity	0% to 10% lower	5% to 15% lower	None recommended
CTE*	0% to 30% greater	0% to 30% greater	Reduce panel size
Drying shrinkage	20% to 50% greater	70% to 100% greater	Reduce panel size
Creep	30% to 60% greater	30% to 60% greater	Typically not an issue in pavement applications
Bond strength	Similar to conventional concrete, or slightly less		None recommended
Permeability	0% to 500% greater	0% to 500% greater	Reduce w.cm ratio

*CTE = coefficient of thermal expansion

There are two common ways to manage this issue. The first is moisture conditioning, achieved by pre-wetting the RCA before mixing so it reaches a saturated surface-dry (SSD) condition (Tam and Le 2007). In that state, the aggregate neither absorbs water from the paste nor adds free water to it, so the mixture behaves more consistently. The second is to apply a water correction factor during mixture design, adding the extra free water needed to account for absorption and adjusting batching accordingly (Xiao et al. 2012a). Both methods depend on knowing the actual absorption of the specific RCA batch, which is why characterization testing is an essential part of mixture design rather than a separate step and it compensates for RCA's weaker ITZ (see Section 4.2.1) and ensures low permeability for the exposure conditions.

Water-reducing admixtures and superplasticizers can also help (Olorunfemi and Ofuyatan 2023). They improve workability at lower water content, which increases strength and improves durability. Combining fly ash at a 20% replacement rate with a superplasticizer can reduce water demand in RCA concrete by up to 12.5% compared with a plain RCA mixture (Saravana Kumar and Dhinakaran 2012). This approach is especially useful when the RCA absorption is near the upper end of acceptable limits.

5.4—Workability and fresh properties

Beyond elevated water demand, RCA concrete's fresh properties differ from conventional concrete mixtures in ways that significantly impact batching, placement, and finishing. Workability drops due to both higher absorption and the angular, rough texture of RCA particles, which increase internal friction (Sobuz et al. 2024). Residual calcium hydroxide in RCA can also accelerate early stiffening and slump loss by reacting with fresh cement (Obla et al. 2007). This means that mixtures that appear workable at the batch plant may lose slump more quickly during transport than conventional concrete, posing practical challenges for ready-mixed concrete delivered to sites more than 20 to 30 minutes away (Abkulut 2025).

Air content typically rises by 4–6% in RCA mixtures compared to equivalent natural aggregate mixtures, partly from air voids in the adhered mortar that crushing doesn't fully remove (Topçu and Şengel 2004). When testing air content, the pressure method can overestimate the result because it does not distinguish between air in the cement paste and the open porosity of the aggregate itself. For highly absorptive RCA, the volumetric method is more reliable (ACPA 2009).

Recycled Concrete Aggregate typically reduces bleeding in fresh concrete because the high absorption capacity of the adhered mortar limits the free water available to migrate to the surface. While this reduction reduces the risk of water trapping under aggregate, it can negatively impact finishability, particularly when fine RCA is used, leading to a harsher, less plastic mixture, and hand finishing can become difficult. Mechanical finishing equipment largely resolves this issue and is standard practice in pavement applications, but this behavior is worth noting for applications where hand finishing is anticipated (Silva and Dhir 2014).

Setting accelerates too, with hydrated cement and calcium hydroxide in RCA shortening initial and final set times by 30–60 minutes versus conventional mixtures (Obla et al. 2007; Richardson et al. 2011). In hot weather, where short set times are already a concern, demands retarding admixtures in the design (Tam et al. 2021).

5.5—Strength—What to expect and how to manage it

The concrete mixture designer has the same main tools available as in conventional high-performance concrete. The most effective single measure remains reducing the water-to-cement ratio, which directly boosts strength while countering RCA's inherent weaknesses like higher porosity and weaker bonding.

Supplementary cementitious materials, fly ash, slag, and silica fume, improve paste density and help compensate for the weaker ITZ around RCA particles (Wang et al. 2023). Fly ash, in particular, reacts more slowly to fill microcracks over time, while GGBS accelerates early strength gain through its higher reactivity—both are widely used in RCA mixtures at 20–40% cement replacement levels with proven benefits for long-term durability (Topçu and Şengel 2004; Adams and Jayasuriya 2019). Silica fume offers the most aggressive refinement but demands careful dosing to avoid excessive viscosity.

Fiber reinforcement also plays a key role. Steel or polypropylene fibers (0.5–1.5% by volume) bridge cracks at the ITZ, enhancing tensile capacity and toughness—especially valuable since RCA concrete shows 15–25% lower splitting tensile strength than natural aggregate mixtures (Richardson et al. 2011). High-range water reducers paired with these strategies maintain workability without excess water.

5.6—Durability considerations

As established in Section 4.1.3, RCA exhibits higher porosity than natural aggregate. This elevated porosity creates more pathways for water, chlorides, sulfates, and carbon dioxide, accelerating long-term degradation mechanisms (Ghorbel and Amiri 2019).

Carbonation penetrates deeper in RCA concrete due to additional ITZ and higher porosity, bringing the carbonation front closer to reinforcement faster and shortening the time to corrosion initiation (Castorena et al. 2012). Chloride ingress follows the same pattern, which is particularly problematic in marine or de-icing salt environments (Lian et al. 2022). Low water-to-cement ratios and the inclusion of SCMs, particularly fly ash and silica fume, are the most effective countermeasures, both of which reduce permeability and refine pore structure (Wang et al. 2021). Concrete mixtures with multi-SCMs can reduce chloride permeability by up to 68% compared to conventional concrete, and the incorporation of fly ash and metakaolin improves resistance to chloride ion penetration in marine exposure environments (Ghorbel and Amiri 2019).

Freezing-and-thawing resistance varies. If the source concrete had good air entrainment, RCA retains some protective air voids, but aggregate-level mass losses remain higher: 1–12% more for coarse RCA and 10–33% more for fine RCA versus natural aggregates (Gokçe et al. 2011; Lotfy and Al-Fayez 2015; Liu et al. 2024). Properly designed RCA concrete can achieve satisfactory durability in pavements exceeding 15-year service with adequate air entrainment (FHWA-HIF-22-020 2022). Proper air entrainment in the new mixture remains essential.

Alkali–aggregate reactivity (AAR) presents a distinct challenge when using RCA. If the original concrete was affected by AAR, the recycled aggregate may still contain reactive silica, allowing the reaction to persist. This risk is particularly pronounced in fine RCA due to its higher surface area. To mitigate these effects, standard approaches include the use of SCMs to limit available alkalis, blending with non-reactive aggregates, and adherence to established protocols such as AASHTO R80. In cases where AAR is a concern, petrographic analysis of the RCA source material is recommended (Li and Gress 2006; Adams et al. 2013).

D-cracking caused by freezing-and-thawing of aggregate particles with high absorption and poor soundness—may occur if the source concrete contained susceptible aggregates. However, the overall volume of coarse aggregate in RCA is lower than in conventional concrete (because each particle is a mixture of aggregate and mortar), which dilutes the risk somewhat. Long-term field observations of RCA pavements containing potentially susceptible aggregates have shown generally satisfactory performance over decades (Smith et al. 2009).

5.7—Shrinkage, creep, and volumetric stability

RCA concrete shows 25–35% higher creep and shrinkage than conventional concrete mixtures (Domingo-Cabo et al. 2009; Sagoe-Crentsil et al. 2001). At 90 days, drying shrinkage in RCA concrete ranges from 0.55 to 0.8 mm/m, compared with approximately 0.3 mm/m for natural aggregate concrete (Yang, Y. et al. 2008b). The difference is driven by the elevated mortar content. RCA concrete contains both old mortar adhered to the recycled aggregate and new mortar of the mixture, giving a total mortar content substantially higher than that of equivalent conventional concrete. Since mortar shrinks more than aggregate, higher mortar content directly means higher shrinkage.

Fine RCA increases shrinkage, because its larger surface area has greater proportion of adhered mortar per unit volume compared to coarser RCA; therefore, driving higher shrinkage rates. That is another reason to limit and carefully control fine RCA content in mixture design (Evangelista and de Brito 2007).

Standard shrinkage controls work well: lower paste volume, reduced w/c ratio, fly ash, and water reducers all reduce shrinkage significantly (Zhu and Wu 2010). Extended moist curing is especially critical for RCA's porous matrix, which loses moisture rapidly. For rigid pavements, measure coefficient of thermal expansion (CTE) per AASHTO T 336 rather than assuming source concrete values. CTE depends on both reclaimed aggregate and total mortar volumes.

5.8—A practical approach to mixture design with RCA

A good RCA mixture design starts with testing each batch for density, water absorption (see Section 4.1.2), and particle size distribution. Using assumed or average values introduces systematic error into every calculation. Testing for contaminants like sulfates, chlorides, and organics is also recommended, especially with undocumented sources (Adams and Jayasuriya 2019).

Once absorption is measured, calculate the effective free water content (FHWA_HIF-22-020 2022). Whether managing it through pre-wetting or water correction factors, adjustments must use actual values, not defaults, refer to Section 5.3.

Supplemental cementitious materials should be considered as standard rather than optional additions (McNeil and Kang 2013). Fly ash, slag, and silica fume all improve the microstructure of the paste and reduce permeability, which directly addresses the durability weaknesses introduced by the elevated porosity of RCA, refer to Section 5.6. The appropriate type and dosage depend on the application and exposure conditions, but incorporating at least one SCM is good practice in any RCA mixture intended for structural use.

Trial batching is not optional. The interactions between RCA absorption, paste chemistry, SCM reactivity, and admixture performance are complex such that calculated mixture proportions should be verified experimentally before any significant commitment to production (Adams and Bandelt 2022). This is particularly true for the first time an RCA batch from a new source is used, and whenever there is any change in aggregate supplier or processing method.

5.9—Summary of key property differences

The use of RCA introduces a range of material and performance differences compared to conventional concrete, primarily due to the presence of residual mortar and its associated effects on density, absorption, and porosity. These differences influence key fresh and hardened properties, including workability, setting behavior, shrinkage, and durability. However, with appropriate mixture design adjustments and construction practices, many of these challenges can be effectively managed. Table 5.9a summarizes the principal distinctions between conventional and RCA concrete, along with practical mitigation strategies used to address them.

Table 5.9a—RCA vs conventional concrete — key differences and mitigation measures (Sources: Limbachiya et al. (2000); Etxeberria et al. (2007); Hansen and Narud (1983); Obla et al. (2007); ACPA (2009))

Property	Conventional	RCA Concrete	Key Mitigation
Water absorption (agg.)	0.5–2%	3–10%	Pre-wet aggregate; water correction factor
Workability	Good	Reduced	WRAs; superplasticizers; moisture control
Setting time	Baseline	30–60 min faster	Set-retarding admixtures if required
Drying shrinkage (90d)	~0.3 mm/m	0.55–0.8 mm/m	Low paste content; fly ash; WRAs; curing
Air content	Baseline	+4–5.5%	Volumetric air test preferred
Durability (permeability)	Baseline	Higher permeability	Low w/cm; SCMs; adequate cover
Freezing-and-thawing resistance	Baseline	1–33% higher loss	Air entrainment; low w/cm; SCMs

5.10—Conclusion

Recycled concrete aggregate is not a drop-in substitute for natural aggregate. Using it well, necessitates a more deliberate approach to mixture design than most engineers apply when working with conventional materials. It requires more testing upfront, more careful water management, lower water-to-cement ratios, and a realistic understanding of how properties will shift as replacement levels increase.

The adjustments are well understood and manageable. Decades of research have moved RCA concrete beyond "whether it works" to "how carefully you've characterized your specific material and translated that into mixture design." Poor outcomes almost always come down to two things: skipping adequate testing or applying conventional mixture assumptions without adjustment.

For the right applications, properly designed, batched, and cured RCA concrete reliably meets structural, workability, and durability requirements. The engineering knowledge exists. Success comes down to consistent application. For pavements, RCA requires design adjustments for lower elastic modulus, higher thermal expansion, and reduced unit weight. Standard sulfate soundness tests are unreliable for RCA; use AASHTO M 319 instead. With proper adjustments, no significant barriers prevent higher RCA replacement levels in rigid pavements.

6—Applications and structural performance of recycled concrete aggregate



Source: Daily Journal of Commerce April 28, 2026

Recycled concrete aggregate provides a practical means of managing the large volumes of concrete debris generated by the Syrian conflict. However, it is not a uniform material; its properties vary depending on the source concrete and the processing methods used, making proper testing essential. RCA can be used across a wide spectrum of applications, ranging from low-value uses such as road base and fill to higher-value applications like structural concrete and pavements. It is important to distinguish true recycling from downcycling, as confusing the two can obscure the more stringent engineering requirements associated with structural use.

Many applications do not require the full performance of high-quality quarried aggregate (ACPA 2009). In lower-strength concrete, non-structural elements, foundation work under moderate exposure, road sub-base layers, and residential pavement applications, RCA can meet design requirements at lower cost and with clear environmental benefits (ACPA 2009, Hansen 1986). When RCA is sourced locally, the reduction in quarrying, transportation, and landfill disposal can produce substantial embodied-carbon savings.

Structurally, RCA beams perform well. Ultimate moment capacity matches conventional concrete. Deflections increase but remain within code limits. Crack widths and spacing meet design standards, though cracking moments are lower—warranting further research.

6.1—Introduction

The Syrian conflict has generated large volumes of concrete debris, presenting both challenges and opportunities for sustainable waste management. Recycled concrete aggregate provides a practical solution by processing this material for reuse in new construction. While the concept is straightforward, effective implementation requires careful control and proper engineering practices.

Because RCA properties vary significantly (see Chapter 4), its use requires project-specific characterization. These factors influence key properties such as density, water absorption, strength, and durability (see Section 4). As a result, RCA must be properly tested and characterized before use, rather than assumed to be a standard aggregate (Hu et al. 2022).

This section reviews the current state of knowledge in two areas. First, it examines the various applications where RCA has been successfully used, including structural concrete, pavements, road base, and environmental applications. Second, it evaluates the structural performance of RCA concrete, focusing on its behavior under load and the applicability of existing design standards. Pavement-specific considerations and overall conclusions are also presented.

6.2—Applications of recycled concrete aggregate

The range of applications for RCA is broader than many practitioners initially assume. It spans the full spectrum from unbound sub-base material at the lower end to structural concrete and reinforced pavement systems at the higher end. The key is understanding the distinction between processed and unprocessed material, and between applications that fully use RCA's properties versus those that are simply diverting waste.

6.2.1 *Structural concrete production*

The most technically demanding application and the one with the greatest structural consequences is the use of RCA as a partial or full replacement for natural coarse aggregate in new concrete mixtures. Several countries have established formal criteria on replacement ratios for structural concrete under different exposure classes. These are summarized in Table 6.2.1a. Germany's DAfStb guidelines permit up to 45% coarse RCA replacement in non-aggressive exposure classes, reducing to 25% in chemically aggressive environments. RILEM's Type 2 classification permits up to 100% coarse replacement. The UK's BS EN 12620 is considerably more conservative, limiting coarse replacement to 20%. Fine RCA is generally not permitted or strictly limited in most jurisdictions.

For practitioners seeking design guidance, Dillmann 1998, proposed generalized mixture design rules that account for RCA's water absorption and higher porosity (see Sections 4.1.2 and 4.1.3), including design charts for predicting compressive strength.

Table 6.2.1a—Criteria for RCA replacement ratios in structural concrete across by country and exposure class (Source: McNeil and Kang 2013)

Country / Standard	Exposure Class	Max Coarse RCA (%)	Fine RCA
Germany (DAfStb 1998)	X0, XC1–XC4	≤ 45%	Not permitted
	XF1, XF3	≤ 35%	Not permitted
	XA1	≤ 25%	Not permitted
RILEM (1994) – Type 2	All	(≥ 4 mm) ≤ 100%	Not permitted
Netherlands (NEN 5950)	All	≤ 20%	≤ 20%
Belgium (CRIC 2004)	All	≤ 100%	Restricted
Denmark (DS 481)	All	≤ 100%	≤ 20%
UK (BS EN 12620)	All	≤ 20%	Not permitted

In the United States of America, state departments of transportations have different requirements, but tend to be conservative. Generally, they allow coarse RCA replacement of 20-50% without significant structural changes, while limiting fine RCA to lower levels (often < 20%) due to higher water demand. A recent review by Lu (2024) similarly identified 20% as the optimal replacement ratio for balancing mechanical performance with sustainability in structural concrete. For high-strength or exposed structural concrete, limits are lower to manage permeability and elasticity. Because trial batching of RCA concrete is often impractical during the early design stages, design parameters should be estimated based on anticipated material properties derived from available research, historical data, and RCA source characteristics. For empirical pavement design applications, recommended input values reflecting typical RCA concrete behavior are provided in Table 6.2.1b.

Table 6.2.1b—Suggested inputs for empirical rigid pavement design using RCA concrete (Source: AASHTO July 2008 Interim Edition; ACPA (2009)).

Input Type	Input	RCA used as Coarse Aggregate	RCA used as Coarse and Fine Aggregate	Suggested Test Protocol and/or Additional Information
PCC	Poisson's ratio	Similar to mixture with virgin aggregates		ASTM C469/C469M
	Thickness	Select based on user preferences		
	Unit weight	0% to 10% lower	5% to 15% lower	AASHTO T 121
PCC Thermal	CTE	0% to 30% greater	0% to 30% greater	AASHTO T 336
	Thermal conductivity	0% to 40% lower (Bravo et al. 2017)		ASTM E1952
	Heat capacity	Somewhat higher (Damdelen et al. 2014)		ASTM D2766
PCC Mixture	Aggregate type	Select based on actual or expected aggregate source		
	Cementitious material content	Select based on actual or expected concrete mixture design		
	Cement type	Select based on actual or expected cement source		
	w/cm ratio	Select based on actual or expected concrete mixture design		
	Curing method	Select based on agency recommendations and practices		
	Reversible shrinkage (%)	Estimate using agency historical data or select M-EPDG defaults		
	Time to develop 50% of ultimate shrinkage	Estimate using agency historical data or select M-EPDG defaults		
Strength and Modulus	Elastic modulus	10% to 33% lower than mixture with virgin aggregates	25% to 40% less than mixture with virgin aggregates	ASTM C469
	Flexural strength	Achievable with reduced w/cm ratio	—	AASHTO T 97
	Indirect tensile strength (CRCP only)	Achievable with reduced w/cm ratio	—	AASHTO T 198

CRCP = continuously reinforced concrete pavement M-EPDG = Mechanistic-Empirical Pavement Design Guide: A Manual of Practice.

6.2.2 *Road base and sub-base*

Most RCA ends up as base and sub-base material for roads, making it the largest single application worldwide. Particle sizes in the range of 20–50 mm are used as unbound base course material beneath pavement surfaces. In this role, RCA's angular particle shape from the crushing process, is actually an

advantage: angular particles interlock under compaction more effectively than rounded natural gravels, producing a stable, well-interlocked base layer (Pourkhorshidi et al. 2020).

RCA needs to achieve adequate bearing capacity and resist deformation under traffic loading, which it meets in most cases, and the relatively higher porosity and lower strength of the mortar fraction are not limiting factors. In fact, stabilized base applications require less cement binder than with natural aggregate, which can also offer cost advantages.

For sub-base layers beneath rigid or flexible pavements, processed RCA is appropriate. For bulk fill and hardcore beneath structural slabs or embankments, even unprocessed RCA, where larger fragments that have not been crushed to a graded aggregate, can be used effectively.

6.2.3 *Pavement construction*

Key considerations for pavement design include the lower elastic modulus of RCA concrete compared to the conventional concrete, which depends on replacement level and RCA quality, modified coefficient of thermal expansion, reduced unit weight, and potential for increased drying shrinkage. For empirical pavement design, the parameters directly influence structural layer calculations; therefore, values derived from virgin aggregate experience cannot be applied without prior adjustment (Gabr and Cameron 2012; Pourkhorshidi et al. 2020). Bekoe et al. 2010, similarly found that while elastic modulus decreases with RCA content, flexural strength and CTE remain comparable to conventional concrete. Table 6.2.1b summarizes recommended design input adjustments for rigid pavement design incorporating RCA.

For continuously reinforced concrete pavements, reinforcement quantities may need to be increased to account for RCA's lower tensile strength and elastic modulus, which affect crack spacing and crack width control (Snyder et al. 2018). Pavement thickness design may also need to be marginally increased relative to a conventional concrete alternative at the same target performance level.

6.2.4 *Non-structural and engineered fill applications*

Beyond its use in structural concrete and paving, RCA is highly versatile for various fill and engineered earthwork applications. Large concrete fragments, sometimes referred to as urbanite, can be used directly as building stones, retaining wall elements, or eco-blocks without further processing. Intermediate-sized crushed material (20–50 mm) is appropriate for drainage layer fill, aggregate base beneath floor slabs, pipe bedding, and general hardcore.

One important caution applies to pipe bedding. Some regulations restrict RCA in drainage or filtration due to concerns about potential, specifically elevated pH from residual calcium hydroxide or trace heavy metals. Consequently, local regulations should be consulted before specifying RCA near water-sensitive environments (Gupta et al. 2018).

RCA is a reliable alternative to natural fill for structural applications like foundation pads and road embankments, offering comparable performance across most site conditions (Federal Highway Administration 1997; Aoki and Watanabe 2025; Sharma and Shrivastava 2023). Its angular shape produces good compaction characteristics and its lower unit weight can be an advantage in applications where reducing load on soft ground is a design objective.

6.2.5 *Erosion control and environmental applications*

Large-fragment RCA has been used successfully as riprap for erosion control applications, including riverbanks stabilization, breakwaters, and shoreline protection, see Fig. 6.2.5. The angular, irregular geometry of broken concrete elements provides good hydraulic resistance and interlocking stability (ACI PRC-555).



(a) (b)

Fig. 6.2.5—Recycled concrete aggregate used as riprap (a) Riprap to armor shorelines against scour and water erosion (Source: Garland & Garland), (b) Riprap to protect a streambank from erosion (Source: Wikipedia)

6.2.5.1 Environmental restoration

RCA has demonstrated practical value in environmental restoration and treatment applications. Concrete elements, such as culvert sections, footing fragments, and irregular debris, have been strategically placed to form stable, habitat-friendly structures for marine colonization, see Fig. 6.2.5.1. The rough and angular surface texture of the material enhances habitat complexity, while the mildly alkaline surface chemistry of hydrated cement paste has been identified as potentially beneficial for calcifying organisms that rely on carbonate precipitation (Yen, Chen, and Liu 2001; ACI PRC-555).

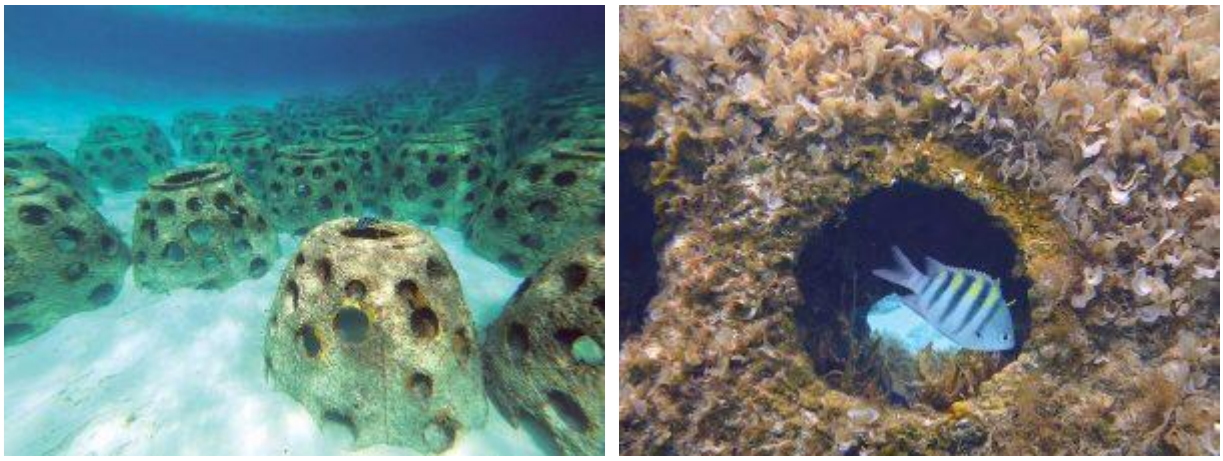


Fig. 6.2.5.1—Reef Balls—concrete structures designed to grow coral and attract fish—are arranged off Malcolm's Road Beach on the western side of Providenciales (Source: Craft 2023).

6.2.5.2 Water and wastewater treatment

In water and wastewater treatment, the alkaline chemistry and high surface area of RCA have been explored as a low-cost sorbents for phosphorus removal from wastewater sewage. The calcium hydroxide present in RCA reacts with phosphate ions to form insoluble calcium phosphate compounds, reducing the risk of eutrophication in receiving waters (ACI PRC-555)

6.2.5.3 Gas treatment

In gas treatment applications, the same alkalinity makes crushed concrete a viable candidate for adsorbing acidic gases, like nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and fluorine compounds. The basic calcium phases neutralize these acidic pollutants, converting them to stable calcium salts and

providing a potential pathway for utilizing RCA as a low-cost sorbent in industrial flue gas treatment systems (Yen, Chen, and Liu 2001; ACI PRC-555).

6.2.6 *Soil stabilization and amendment*

Recycled concrete aggregate strengthens weak or saturated soils through several effective mechanisms. Residual cement in the RCA releases calcium ions (Ca^{2+}), which interact with clay particles reducing repulsion between particles and allowing them to come together and form a more stable, granular structure. As a result, the soil becomes easier to work with and gains short-term strength. Additionally,, this residual cement continues to hydrate, absorbing excess moisture to improve both soil stiffness and strength (Tavakol et al. 2025; Tavakol et al. 2019).

The calcium compounds in RCA also raise the soil pH, promoting the dissolution of silica and alumina, which then react to form cementitious compounds that improve the soil's long-term strength and stiffness. These processes are similar to those used in traditional soil stabilization with lime, fly ash, or cement, but RCA produces weaker and less uniform effects because its cementitious content is lower and depends on the source material (Tavakol 2019; Gangu and Shankar 2024).

In practice, RCA is often used to improve subgrade soils for road construction, especially when local soils are too weak or plastic. RCA combined with fly ash and Portland cement, improved clay soil strength, stiffness, and shrinkage properties. Scanning electron microscopy revealed that RCA produced low void space and dense arrangement of soil particles (Tavakol et al. 2025). Its performance can be further improved by combining it with small amounts of lime or fly ash, which enhances the overall stabilization effect (Gangu and Shankar 2024; Tavakol et al. 2019).

6.2.7 *Geopolymer and novel construction materials*

Crushed concrete fines and dust, which are rich in silicon with moderate aluminum content, have been investigated as potential precursors for geopolymer production (Nikmehr et al. 2022). When combined with metakaolin and alkaline activators, RCA-derived material can produce geopolymer binders suitable for lightweight concrete, insulating concrete elements, and masonry products such as bricks and blocks (Chen et al. 2023).

Geopolymer concrete produced from waste concrete is well suited for applications requiring moderate compressive strength combined with low density or thermal insulation. Higher aluminosilicate content (metakaolin and slag) improves the mechanical properties of hardened geopolymer concrete but may reduce workability, making mixture optimization essential (Nikmehr et al. 2022). This technology remains largely at the research stage in most markets, though the chemistry is well understood and laboratory-scale production has been demonstrated.

6.3—Structural performance of RCA reinforced concrete members

Understanding the material properties of RCA concrete is necessary but not sufficient for structural engineering decisions. What ultimately matters is how those changed material properties translate into full-scale member behavior under load. The research literature on RCA beam performance is extensive enough to draw clear conclusions about deflection, crack behavior, and moment capacity. Those conclusions are broadly reassuring, with some important qualifications.

6.3.1 *Midspan deflection under service loading*

Service-load deflection is a critical serviceability criterion for beams. The main concern is that RCA concrete's elastic modulus is typically 10–40% lower than that of equivalent natural aggregate concrete, depending on replacement level and source quality . A lower elastic modulus means greater deformation under the same applied load.

Fathifazl et al. (2009) found that under a load of 40% of the failure load, midspan deflections in RCA beams were measurably greater than in equivalent natural aggregate beams. Maruyama et al. (2004), Sato et al. (2007), and Knaack and Kurama (2020) independently confirmed that RCA beams consistently deflect more, and Sato et al. noted that this finding held regardless of RCA source, original concrete quality, or curing method.

Despite the increased deflections, predicted values from ACI 318, Eurocode 2, and the moment-curvature method remain conservative relative to observed behavior. Current design provisions, applied with appropriate material input values, continue to provide an adequate safety margin for deflection control. The increased deflection is real but remains within what the codes anticipate.

6.3.2 *Crack width and crack spacing*

Cracking behavior in reinforced concrete beams constructed with RCA beams shows a consistent pattern to those observed in conventional concrete, with slightly wider crack widths and slightly narrower crack spacing. Maruyama et al. (2004) documented this and noted that the differences were small from an engineering perspective, and that observed crack widths remained well below applicable code limits. Sato et al. (2007) confirmed the same relationships and added that dry-cured beams exhibited smaller crack spacing than wet-cured beams, again without significant structural consequence.

These behaviors are commonly attributed to the microstructure of RCA concrete, which contains two ITZs. As discussed in Chapter 4, these ITZs represent the weakest regions in the composite material and serve as preferred paths for crack initiation and propagation. The presence of a “double ITZ” system can lead to earlier crack initiation and a greater number of cracks, which are typically slightly wider than those in conventional concrete. Despite these effects, available research suggests that existing design provisions for crack width and spacing remain applicable to RCA concrete (Xiao et al 2012c).

6.3.3 *Flexural capacity: cracking moment and ultimate moment*

Two distinct moment parameters are relevant to beam design: the cracking moment and the ultimate moment. RCA affects these two parameters quite differently.

The cracking moment is more sensitive to RCA incorporation than the ultimate moment. This is because cracking depends on the concrete’s tensile strength, specifically the modulus of rupture and splitting tensile strength, both of which are reduced by the double ITZ and the weaker mortar fraction in RCA concrete. RCA concrete generally exhibits slightly lower cracking moments than comparable natural aggregate concrete (Fathifazl et al. 2009). Their findings suggest that splitting tensile strength provides a closer estimate of cracking moment than the modulus of rupture, though both are valid. Therefore, current code provisions remain applicable; however, the shift in predictive accuracy suggests that additional research may be beneficial, particularly for high RCA replacement ratios (McNeil and Kang 2013).

The ultimate moment of RCA and natural aggregate reinforced concrete beams is essentially the same. Kang et al. (2012) showed that if concrete strengths were held equal, the difference in moment capacity between RCA and natural aggregate beams was negligible, and that this difference was effectively zero when the RCA replacement ratio was held below approximately 3/7 of the total coarse aggregate volume by weight. Maruyama et al. (2004) found that all experimental ultimate moments exceeded code predictions by 10–20%, providing an additional margin of safety. Sato et al. (2007) concluded that 'the ultimate moment can be predicted using Japanese codes irrespective of the type of original aggregate and original concrete.

The consistency of this finding across different research groups, different RCA sources, and different code frameworks is particularly significant. Ultimate flexural capacity is not a limiting concern for RCA

use in reinforced concrete beams. Provided the member is designed so that steel yielding governs failure, which is standard practice for ductile structural design; the change in aggregate does not meaningfully reduce load-carrying capacity.

6.4—Pavement design considerations

Pavement design with RCA requires more detailed approach to material properties than typical structural design. Because empirical design methods use concrete properties in performance models, rather than as general guidelines for sizing, the results are sensitive to inputs (Disfani et al. 2014). For example, a 15% reduction in elastic modulus affects directly pavement thickness calculations and cannot simply be ignored or mitigated by a standard safety factor (Pourkhorshidi et al. 2020).

Where trial batching is unavailable early on, default ranges from the literature, such as Table 6.2.3, offer a reasonable basis for preliminary design. These should be treated as conservative estimates pending actual material testing, and the final pavement design should be verified against measured properties before construction.

Qualification testing for RCA in pavement generally follows virgin aggregate protocols, but key modifications are necessary. Standard sulfate soundness tests (sodium or magnesium sulfate) often produce unreliable results for RCA because the adhered mortar reacts with the sulfate solution, causing artificially high mass losses that overstate deterioration susceptibility. Instead, AASHTO M 319 provides alternative soundness evaluation methods appropriate for RCA. Abrasion testing per AASHTO T 96 (Los Angeles test) is applicable, but some agencies permit higher allowable loss percentages for RCA than for virgin aggregate, recognizing that the mortar fraction is inherently softer.

If the source concrete is prone to alkali-silica reaction (ASR) or D-cracking, it is necessary to run additional tests per AASHTO R 80. However, D-cracking is less of a concern in RCA concrete because each particle is a composite of aggregate and mortar, reducing the volume of susceptible aggregate per unit volume of concrete. Several projects where D-cracking susceptible sources were used, RCA pavements performed well over decades of service (Gomez-Soberon 2002, Butler et al. 2012).

Contaminant limits set by the ACPA provide a practical framework for quality control in pavement RCA. Recommended maximum contents include asphalt concrete at 1% by volume, gypsum at 0.5% by weight, glass at zero, and chlorides not exceeding 3.5 N/m³. Washing and air blowing during processing are effective tools for reducing dust, fine contaminants, and organic material that would otherwise interfere with air entrainment and paste chemistry.

6.5—Conclusion

RCA is a versatile material, used for applications ranging from road base and fill to structural concrete and pavement. It further serves specialized functions in erosion control, soil stabilization, and emerging environmental technologies. Prioritizing high-value recycling, however, requires strict engineering standards.

Research consistently shows that using RCA does not significantly impact the ultimate moment capacity of structural beams designed for ductile failure. While the lower elastic modulus of RCA concrete leads to increased deflections, these remain well within code-compliant limits. Crack widths and spacings show slight variations but still meet design standards. The most notable difference is in cracking moments, suggesting that further research to improve predictive models in this area is needed.

When designing pavements, it is essential to input the unique mechanical and thermal properties of RCA into mechanistic-empirical models. Qualification testing should also include specific adjustments

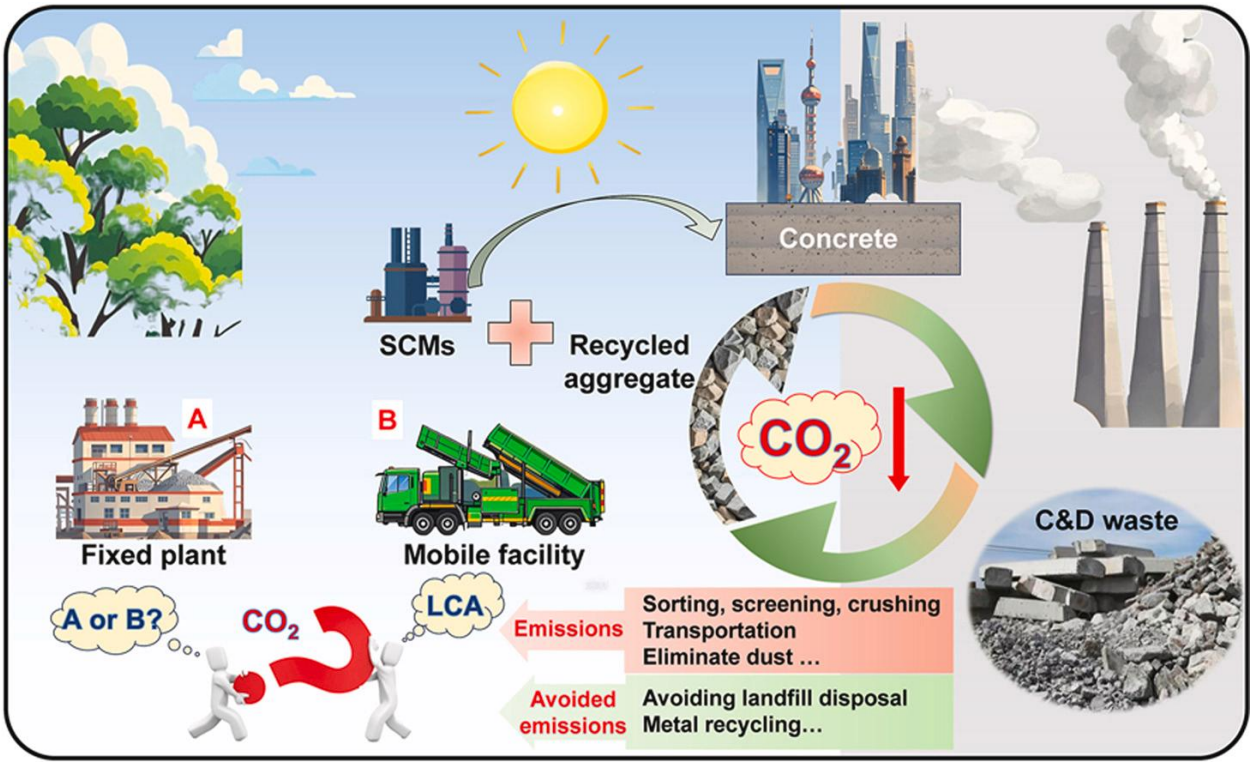
for soundness and alkali-aggregate reactivity (AAR). With these modifications, there are no significant technical barriers to adopting higher replacement levels of RCA in rigid pavement systems.

The suitability of RCA for construction applications depends largely on aggregate size and source quality. Table 6.5 provides a general overview of typical uses, recommended gradations, and observed performance.

Table 6.5—Summary of RCA Applications with Recommended Aggregate Sizes and Performance Notes

Application Type	RCA Size	Description/Notes
Road Base/Sub-base	20–50 mm	Unbound material for highways, pavements, and civil engineering projects
Structural Concrete	0–50 mm	Partial replacement (up to 30%) of natural aggregates; maintains 85–95% of NA concrete strength
Riprap/Shoreline Protection	Large fragments	Erosion control, rock armor, breakwaters
Fill/Hardcore	20–50 mm	General construction fill and leveling material
Cement Recovery/Flux Material	Pulverized fines	Reactivated cement via electric arc furnace; reduces CO_2 emissions

7. Environmental benefits and sustainability of recycled concrete aggregate



Source: Ma, et al. 2025

Recycled concrete aggregate is a practical, eco-friendly solution, that successfully balances economic feasibility with crucial environmental preservation in modern construction. Global market experience has proven that RCA benefits—reducing landfill pressure, lowering carbon emissions from material transport, and conserving virgin aggregates—are not just theoretical but measurable and real. To fully realize these benefits, RCA must be recognized as an engineered material requiring rigorous characterization and disciplined on-site controls.

Nowhere is this balance more urgent than in Syria. After more than a decade of conflict and the 2023 earthquake, entire districts of cities like Aleppo, Homs, and Raqqa have been reduced to concrete rubble. The instinct to clear and bury this material would be an environmental tragedy—consuming scarce landfill space, wasting embodied energy, and missing a chance to rebuild with a lower carbon footprint. For Syria's reconstruction to be both resilient and responsible, RCA must be adopted not as a symbol of recycling, but as a disciplined, site-specific engineering strategy. When done right, it transforms environmental liability into foundational asset, turning the debris of war into the base of a sustainable recovery.

7.1—Introduction

Rebuilding Syria requires a sustainable approach to construction, as the industry is poised to be a major consumer of natural resources and a top generator of waste and emissions. RCA offers a significant opportunity to build back more sustainably, by turning rubble and crushed concrete into new, high-quality aggregate and reducing dependence on virgin resources.

This section evaluates the environmental advantages of RCA, including landfill-waste reduction, natural-resource conservation, carbon-emissions savings, and support for a circular economy, while also addressing carbonation effects and environmental considerations associated with RCA production and use.

7.2—The scale of the problem RCA addresses

Producing RCA is a construction activity that involves large-scale plant operations, large-volume material handling, frequent vehicle movements, significant water use, and residual waste streams such as fines and contaminants. Like any heavy construction activity, it carries environmental risks that must be managed rather than ignored. When owners, contractors, and regulators apply equivalent environmental rigor to RCA operations, the benefits are real, quantifiable, and substantial (Neupane et al. 2025).

7.2.1 *Waste generation and landfill pressure*

Without a comprehensive recycling plan, the massive volume of concrete debris generated by over than a decade of conflict faces would be disposed of in landfills, where its non-biodegradable nature would cause it to remain indefinite. RCA can reduce the amount of C&D waste sent to landfills by 40-60% (Marinković 2010), by:

(a) Reducing the demand for landfill space

(b) Minimizing environmental degradation associated with landfill expansion

(c) Supporting sustainable waste management practices

7.2.2 *Natural aggregate demand and resource depletion*

Natural aggregates such as sand, gravel, and crushed stone are finite resources extracted through quarrying and mining. These operations are associated with:

(a) Habitat destruction and ecosystem disruption

(b) Soil erosion and landscape alteration

(c) Groundwater interference

(d) Dust generation and air pollution

(e) High energy consumption

Because aggregate deposits are geographically fixed and often distant from construction sites, transport by road, rail, or sea significantly increases carbon emissions and traffic congestion. Locally sourced RCA, processed at or near demolition sites using mobile crushing plants, can substantially reduce transport-related emissions compared with natural aggregates (Ma et al. 2025). It is estimated that incorporating C&D waste can reduce natural aggregate consumption by 20–40% without significantly increasing concrete cost or environmental impact (Patil, 2024; Kurda et al. 2018). By replacing natural aggregates with RCA, the construction industry can significantly reduce dependence on virgin materials.

7.3—Carbon footprint and climate implications

Decarbonizing the built environment is a priority in virtually every climate roadmap, yet construction remains one of the hardest sectors to abate. RCA directly reduces the need for quarrying, blasting, hauling, and grading virgin stone by reusing material that has already been extracted and processed. In post-conflict Syria, where entire urban landscapes have been reduced to concrete rubble, this represents a partial redemption of a prior carbon debt rather than a new one.

Transport emissions are further reduced when RCA is processed and used locally within damaged cities, avoiding long-haul trucking from rural quarries that may be inaccessible or insecure. These savings are measurable and verifiable, provided RCA is sourced from clean debris and processed using energy-efficient equipment. On-site or near-site recycling, with mobile crushers operating within damaged districts, can eliminate outbound haulage of waste, inbound haulage of virgin aggregate, and associated quarrying emissions. In a country where fuel is scarce and expensive, these reductions are both environmental and strategic.

7.3.1 *Emissions savings from RCA use*

RCA in concrete production can reduce CO_2 emissions by 20–50% compared with conventional natural aggregate mixtures, primarily by avoiding emissions from aggregate extraction and processing (Prasittisopin et al. 2025). Syrian cities such as Aleppo, Homs, and Idlib face simultaneous challenges: vast concrete debris stocks, destroyed road networks, and a desperate need for affordable aggregate to rebuild housing, schools, and infrastructure. Mobile crushing within affected district offers a practical way to convert these constraints into a resource.

7.3.2 *Carbonation: A secondary carbon sequestration mechanism*

RCA also offers a secondary carbon-sequestration benefit via carbonation. Crushing concrete increases its surface area, exposing unreacted cement paste to atmospheric CO_2 (Kekkonen et al. 2023). The chemical reaction between CO_2 and calcium hydroxide forms calcium carbonate, locking carbon into the material (Kaddah et al. 2022). This carbonation process is enhanced by rain exposure during stockpile storage and continues through the secondary service life of the aggregate (Patrisia et al. 2026). Patrisia, et al. (2026) further quantified that shallow, spread-out stockpiles achieve 31–65% CO_2 uptake of calcination emissions over 12 months, depending on pile configuration and duration. Pressurized CO_2-treatment can further increase compressive strength by up to 42% (Russo and Lollini 2022) and reducing water absorption by around 27%, while sequestering carbon. At a global scale, accelerated carbonation of concrete debris could sequester an estimated 62.5 Mt of CO_2 annually, though net benefits vary significantly by region (Zhang et al. 2022). At pressures of 0.14 MPa and higher, treated RCA concrete can approach the properties of natural aggregate concrete with a lower CO_2 equivalent than untreated RCA (Ismail et al., 2025).

7.3.3 *Role of supplementary cementitious materials*

RCA made from Syria's war-destroyed buildings can replace up to 50% of natural coarse aggregate in new concrete without significantly affecting performance (Rashwani et al. 2023). With an estimated 15 million tons of concrete debris from more than 130,000 destroyed buildings—70% of them reinforced concrete—RCA has substantial supply-side potential (Rashwani et al. 2023). Combining RCA with supplementary cementitious materials (SCMs) is recognized as one of the most effective single strategies within current concrete technology for reducing embodied-carbon emissions by over 40% compared with conventional Portland-cement concrete (Mouna and Suryanto 2025).

7.4—RCA and the Circular Economy

RCA aligns closely with circular-economy principles, including resource efficiency, waste minimization, and continuous material reuse. Concrete recycling supports a partial cradle-to-cradle lifecycle, in which demolished structures are reintegrated into new construction. The highest level of circularity is achieved when RCA directly replaces natural aggregates in new concrete (Younes et al. 2025).

7.4.1 *True recycling vs. downcycling*

Not all uses of crushed concrete represent the same level of circular performance. It is important to distinguish between:

(a) True recycling means using RCA in structural concrete applications, preserving material quality, embodied energy, and contributing to mechanical performance

(b) Downcycling means using RCA in lower-value applications like road base, drainage layers, landscaping, or backfill, where its original structural properties aren't needed. This supports waste reduction and reduces demand for quarried stone, even if it doesn't fully preserve the original material's value (BCPH 2017)

Both approaches are valid and beneficial. Downcycling helps divert waste from landfills and reduces the need for virgin aggregates in suitable applications. However, distinguishing between the two is important. Conflating them can overstate how much RCA is actually being reused in structural applications and may overlook the stricter engineering requirements that come with incorporating RCA into concrete.

Even with high recovery rates, RCA can meet only a portion of total aggregate demand. Full circularity requires complementary strategies, such as alternative binders and materials, improved construction and demolition practices, and sustainable urban planning and design.

With the urgent need to clear roads, rebuild infrastructure, and restore access to damaged neighborhoods, downcycling stands out as Syria's most immediate, practical strategy. Crushed concrete can quickly become unbound base layers for roads into Aleppo, drainage fill to prevent flooding in Homs, or leveling material for temporary shelters in Idlib. These applications require only basic crushing and screening, with lower technical risk than structural alternatives. For a country facing massive debris accumulation, fuel shortages, and a need for rapid stabilization, downcycling offers a low-barrier, effective approach to managing the rubble. As Syrian researchers have emphasized, "debris is not waste — it is raw material" (Al-Swaidani 2025).

The more ambitious pathway is to use RCA in new structural concrete, which has been validated under for Syrian conditions. Research led by the University of Aleppo demonstrated that RCA from war-destroyed Syrian buildings can replace up to 50% of natural coarse aggregate in new concrete without significantly affecting performance (Rashwani et al. 2023). However, this pathway requires proper characterization of feedstock to remove contaminants such as, soil, gypsum, sulfates, and chlorides; quality-controlled crushing and screening; and often the addition of SCMs to improve the ITZ. These requirements are not impossible in Syria, but they demand investment in mobile or fixed crushing facilities, laboratory testing capacity, and trained personnel.

The most pragmatic approach for Syria is a tiered recycling strategy, as shown in Table 7.4.1, that matches material quality to application value.

Table 7.4.1—Proposed implementation of RCA in the reconstruction of Syria

Tier	Application	Quality Requirement	Readiness for Syria
1	Fill, embankments, temporary roads	Minimal crushing, no testing	Immediate
2	Road base, sub-base, drainage	Basic crushing, gradation control	Near-term (6–12 months)
3	Non-structural concrete (sidewalks, curbs, blocks)	Controlled crushing, contaminant screening	Medium-term (1–2 years)
4	Structural concrete (up to 50% replacement)	Full characterization, SCMs, quality control	Medium-term with investment

Syria cannot afford to do nothing or afford to wait for practical conditions. Landfills are scarce, fuel for hauling debris is expensive, and the social cost of leaving rubble in place creates blocked roads, hazardous sites, delayed reconstruction. The choice is not between true recycling and downcycling; it is between active material management and passive waste accumulation. Downcycling today does not preclude true recycling tomorrow. The same stockpile of crushed RCA that serves as road base this year can, with future investment, supply higher-value applications later. What matters is that the material is saved, not buried.

7.4.2 *The concrete life cycle*

The cradle-to-cradle model for concrete is straightforward: produce concrete, use it in structures, demolish at end of life, crush into RCA, and re-incorporate into new concrete. This should occur with minimal quality loss at each cycle. Achieving this requires careful management of each transition (ISO/TS 21056 2025). This ideal requires careful management at every transition. Buildings and structures designed with recyclability in mind—through specified concrete grades and reinforcement configurations that make demolition and aggregate recovery easier—can improve RCA quality decades later. Structures designed today could be demolished in 30–80 years, entering a recycling stream where demand for sustainable materials will likely be even greater than it is now.

7.5—Environmental concerns during RCA production and handling

The environmental case for RCA must not ignore its production footprint. RCA operations generate water-quality risks from alkaline runoff, air-quality issues from dust and equipment emissions, noise and community impacts, and solid-waste residuals from the crushing process. These impacts are not unique to concrete recycling, and all are manageable, but they require proactive planning same as any construction activity of equivalent scale.

7.5.1 *Water quality*

The primary environmental concern associated with RCA is the high alkalinity of its runoff and leachate. Dissolved calcium hydroxide in RCA stockpiles can generate drainage with elevated pH levels, potentially harming vegetation, surface waters, and metal infrastructure, such as zinc-coated pipes, if not managed. Leachate from RCA may also contain trace of heavy metals such as vanadium, chromium, and lead, which can occasionally exceed drinking water standards. However, appropriate stormwater best management practices (BMPs) such as dilution, containment, and treatment generally reduce these concentrations to acceptable levels (ACPA, 2008; Snyder et al., 2018). Biostimulation can reduce initial RCA leachate pH to as low as 8 while enriching anaerobic, halotolerant, and alkaliphile microorganisms capable of surviving extreme conditions (Soleimanifar et al. 2023).

Effective water management depends on careful site planning and stormwater control. RCA stockpiles should be located away from surface water, with runoff managed through perimeter berms, silt fences, vegetated filter channels, and bioswales. Where elevated pH is anticipated, neutralization using CO_2 bubblers, chemical additives, or pH control systems should be implemented before discharge.

In post-conflict Syria, approximately two-thirds of the nation's water infrastructure has been destroyed (Fanack Water, 2025). Rivers and streams remain obstructed, and groundwater monitoring is largely nonfunctional, which displaced populations living in informal settlements have limited access to safe water (Syria Recovery Trust Fund (SRFT) , 2025a). Introducing high-pH RCA runoff containing trace metals into this fragile system would exacerbate water quality risks. Syria's extensive clay-rich soils in the Euphrates Basin and Mediterranean coastal plains can naturally neutrlize alkaline leachate through mineral dissolution and cation-exchange processes, delaying hydroxide migration (Chen et al. 2020; Soleimanifar et al., 2023; Sanger et al., 2020

Given Syria's acute water vulnerability, RCA use must adopt a risk-based approach emphasizing stringent water quality controls from the earliest planning stages, Table 7.5.1.

Table 7.5.1—Risk level to water resources

Risk Level	Setting	Required Controls
High	Proximity to drinking-water intakes, or functioning treatment plant	Full BMP suite: berms, sediment traps, CO_2 treatment, pH monitoring; SWPPP*
Medium	Damaged areas but potentially restorable water infrastructure	Standard BMPs plus soil neutralization assessment and buffer zones
Low	Arid zones with deep clay subsoils or far from watercourses	Basic containment and periodic pH spot-checking

*Stormwater pollution prevention plan, SWPPP, is a site-specific document is developed for construction or industrial activities. It outlines measures to minimize erosion, sediment, and pollutant runoff into waterways. SWPPPs are generally required for projects disturbing over one acre. The document must be updated as site conditions change.

For example, the SRTF has rehabilitation water networks in Darayya, As-Sweida and northern Aleppo, restoring access to reliable water sources for thousands of residents (SRTF 2025a, 2025b). RCA management plans can integrate these efforts by directing neutralized RCA runoff into restored drainage systems instead of being discharged untreated. Moreover,, the same biostimulation processes that lower RCA leachate alkalinity and metal concentrations by enriching anaerobic, halotolerant, and alkaliphile microorganisms, can be deployed at Syrian sites with relatively low technical input (Soleimanfar et al. 2023).

RCA offers a compelling opportunity to turn millions of tons of war debris into reconstruction material, but water quality concerns must be addressed through sound planning and management. RCA stockpiling and processing should be located away from critical watercourses, implement proven BMPs, test soils for natural buffering capacity, and integrate runoff control with national water infrastructure recovery. Done correctly, RCA can help rebuild Syria without adding to its water crisis. Done carelessly, it would trade one environmental disaster for another—and Syria has already suffered enough of both (UNDP 2025; UNOCHA 2025; IFRC 2025).

7.5.2 *Air quality and dust*

Dust is the most visible and community-impactful air quality concern associated with RCA processing. The largest dust sources come from haul trucks on unpaved roads and stockpile areas, and from crushing and screening operations. Equipment emissions are a secondary contributor, comparable to those of large construction sites. Dust control technologies are well established and effective. Water spray bars at crushing points can reduce airborne dust by about 50% at a distance of 10 meters (DETR 2000). Lowering vehicle speeds from 50 km/h to 30 km/h cuts dust generation by 22% (BCPH, 2017). Misting systems and fog cannons capture fine particles, while tarping RCA stockpiles, limiting pile heights, and suspending crushing operations during high-wind periods minimize off-site dust migration. RCA operations should also control exposure to respirable crystalline silica, an occupational hazard. The OSHA respirable crystalline silica standard (29 CFR 1926.1153) sets a permissible exposure limit of 50 $\mu g/m^3$ over an 8-hour work shift and requires engineering controls such as water-spray suppression and enclosed cabs, supplemented by respiratory protection where necessary (OSHA 2017).

A documented silica-control plan, including HEPA-equipped enclosures or filters, strengthens on-site safety. On-site or near-site recycling improves air quality by reducing truck-based emissions and fugitive dust associated with long-haul transport. When demolished concrete is processed where it is generated,

the need for transporting debris and virgin aggregate is eliminated, lowering both dust and fuel-related impacts.

In post-conflict Syria, dust control is both a public health and reconstruction necessity. As Syrian researcher Aref Al-Swaidani (2025) notes, “debris is not waste—it is raw material.” But without proper controls, this material poses serious respiratory hazards. Dust from rubble can contain fine particulates and heavy metals from explosives, threatening vulnerable populations. With healthcare infrastructure heavily damaged, uncontrolled RCA dust would place an unacceptable burden on returning communities.

Syria’s arid climate compounds the challenge. Many affected urban centers—Aleppo, Homs, Damascus, and Raqqa—experience low humidity and frequent winds (Al-Swaidani, 2025), amplifying fugitive dust emissions and facilitate wide-area dispersal. Fortunately, modern mobile crushers validated for Syria rubble can integrate dust suppression systems: water spray bars, misting cannons, and enclosed conveyors (Sheffield Study, 2025). On-site recycling, confirmed as feasible under local conditions, further reduces truck movements—the single largest source of dust.

By adopting proven dust controls—water suppression, speed limits, misting systems, and silica management—RCA processing can be both environmentally sound and socially acceptable. The bottom line: dust from RCA processing is a manageable risk, not an obstacle. Table 7.5.2 summarizes those requirements.

Table 7.5.2—A proposed risk-based dust control framework for Syria

Risk Factor	Recommended Control for Syrian Context
Crushing operations	Water spray bars (~50% dust reduction); misting cannons for large areas
Haul roads	Speed limits (≤ 30 km/h reduces dust by ~22%); watering of unpaved surfaces
High-wind days	Suspend crushing operations; tarp or enclose stockpiles
Worker exposure	Enclosed cabs with HEPA filtration; respiratory protection; silica control plan
Community impact	Locate processing downwind of residential zones; monitor particulate levels

7.5.3 *Noise and community impact*

RCA operations in Syria pose significant noise and vibration challenges because many sites are located near dense residential areas. In cities such as Aleppo, Damascus, Homs, Raqqa, and Darayya, crushing activities are often conducted close to populated neighborhoods (The Syrian Observer 2026). Syria typically relies on mobile crushing units and temporary sites, which rarely include permanent noise-control measures. The Institute of Materials, Minerals and Mining (IOM3 2023) provides comprehensive guidance on debris management in post-conflict settings, emphasizing the importance of early noise planning. International debris-management guidance recommends locating recycling operations away from sensitive receptors such as hospitals and temporary housing, but limited land availability and urgent clearance needs often make this difficult. In such cases, natural terrain, partially collapsed structures, or temporary earth berms can provide effective temporary sound barriers.

In neighborhoods where families are returning and rebuilding, noise is both an environmental and a potential psychological stressor. Pilot sites in Damascus’s Jobar district and Homs’s Bab Amr neighborhood demonstrate the need for careful noise management (Al-Swaidani, 2025). Quieter equipment should be prioritized in RCA processing: Hydraulic concrete crushers produce substantially

lower noise levels than traditional percussive breakers because they apply steady crushing force rather than impact energy (FHWA, 2006). Concrete splitters and multi-cutters also reduce both noise and vibration while maintaining processing efficiency (Al-Swaidani, 2025). These technologies should therefore be specified as standard equipment in recycling contracts.

Operational controls should reinforce equipment selection. Recommended measures include reducing material drop heights, keeping haul routes away from residential streets, and restricting noisy activities to daylight hours. Hydraulic power units should be positioned away from residences and isolated with rubber mounts to reduce vibration transmission. Mobile acoustic barriers or existing rubble can be used as temporary shielding, and residents should be informed in advance of work schedules through a designated community liaison.

Syria's reconstruction efforts can set a higher standard for community-sensitive environmental management. The Hong Kong Housing Authority shows that noise complaints fell sharply after quieter methods, including hydraulic crushers, were introduced, dropping from 109 in 2001/02 to 24 in 2003/04 (FHWA 2006). Similar results are achievable in Syria if quieter technology, careful siting, and community engagement are applied consistently. Noise from RCA processing is a manageable risk rather than a fundamental barrier. With appropriate equipment, site controls, and scheduling, recycling operations can proceed while minimizing disruption to nearby communities (Al-Swaidani 2025; FHWA 2006).

7.5.4 *Solid waste residuals*

The management of solid residuals and wash water from RCA production in Syria should reflect both standard industry practice and the practical constraints of post-conflict reconstruction. In cities such as Aleppo, Damascus, and Homs, large-scale debris processing has generated residual streams typical of RCA operations, including crusher fines, recovered reinforcing steel, and miscellaneous materials such as joint sealants and repair compounds from damaged structures.

Crusher fines vary by crusher type: jaw crushers, commonly used in Syria due to their ability to handle large, irregular rubble, produce fewer fines than cone or impact crushers. However, the mixed composition of war-generated debris—including masonry, concrete, and contaminants—can increase the variability and volume of fines compared to typical demolition waste. Recovered reinforcing steel is an important and valuable by-product. UNDP-supported projects have documented its separation, stockpiling, and reuse, contributing to both waste minimization and local economic recovery.

Wash water and runoff are generally managed using conventional construction-site practices: designated wash areas, temporary containment (lined pits or tanks), and sedimentation controls. In Syria's arid to semi-arid climate, evaporation-based management is especially practical. The fundamental objective remains the same: maximize beneficial reuse of RCA by-products, minimize landfill disposal, and implement practical water management controls that support large-scale reconstruction. Table 7.5.4 summarizes the main environmental concerns and mitigation strategies.

Table 7.5.4: Environmental concerns and mitigation strategies for RCA production (Sources: ACPA (2009); DETR (2000); OSHA (2017); Sadecki et al. (1996); Snyder et al. (2018))

Concern	Primary Risks	Key Mitigation Strategies
Water quality	High-pH leachate; heavy metal runoff; suspended solids	Locate stockpiles away from waterways; use berms, bioswales; and pH treatment; monitor
Air quality—dust	Fugitive dust from crushing, haulage, and stockpile disturbance	Spray bars, misting, haul-road speed limits, stockpile covers, wind barriers, silica plan
Air quality—emissions	Equipment and vehicle exhaust; GHG from haulage	Use on-site recycling, minimize haul distances, maintain fleet; reduce idle time
Noise and vibration	Crushing equipment; heavy vehicle movements	Site away from sensitive receptors; use barriers, chutes, conveyors, and off-peak scheduling
Solid waste residuals	Fines; reinforcing steel; sealants; wash water slurry	Beneficial reuse of fines; designate wash areas; use frac tanks or evaporation ponds; dispose of residuals in compliance with regulations

7.6—Limitations and Honest Assessment

In Syria, the environmental evaluation of RCA must reflect the realities of post-conflict reconstruction. Although RCA offers clear sustainability benefits, field experience and assessments by organizations such as the UNEP and the UNDP highlight several important limitations (Rashwani et al. 2023).

Material quality varies widely. In cities like Aleppo, Homs, and Damascus, demolition waste is rarely uniform or well documented. The waste stream typically contains a mix of reinforcing bars, masonry, and damaged materials—some of which may have been exposed to fire, weather, or contamination during the conflict. This heterogeneity makes RCA properties far less predictable than those from conventional sources (Rashwani et al. 2023).

As a result, broad claims about RCA performance can be misleading without project-specific sorting and testing. Inadequate characterization may lead to the use of contaminated or low-quality material, increasing the risk of durability problems, undesirable leaching, or reduced structural reliability. In Syria, where laboratory capacity and quality control systems may be limited, this reinforces the need for conservative application, such as non-structural fill or subbase layers, unless proper testing confirms suitability (Rashwani et al. 2023).

RCA can supply only a limited share of total aggregate demand. While Syria's large volume of demolition debris creates a temporary surplus of recyclable material, this condition is transitional. As reconstruction advances, demand for aggregates, especially for new concrete production, is likely to exceed the supply of material suitable for higher-value applications. RCA cannot replace quarry-derived aggregate (World Bank 2025).

Processing energy and transport emissions also influence the overall environmental benefit. In Syrian reconstruction projects, UNEP and UNDP guidance emphasizes localized recycling through mobile crushing near demolition sites to reduce haul distances (UNEP, 2024a; UNDP, 2024a). Fuel shortages, damaged infrastructure, and logistical challenges make long-haul transport particularly difficult and environmentally costly. When debris must be moved to centralized processing sites, the advantage of RCA declines and should be evaluated on a project-by-project basis. Overall, Syria's experience confirms a key principle observed globally: RCA delivers its greatest environmental value when it is processed locally, matched carefully to its end use, and supported by adequate quality control. It is an essential

component of sustainable reconstruction, but not a standalone solution. It must be integrated with responsible primary aggregate production and effective material management.

7.7—Conclusions

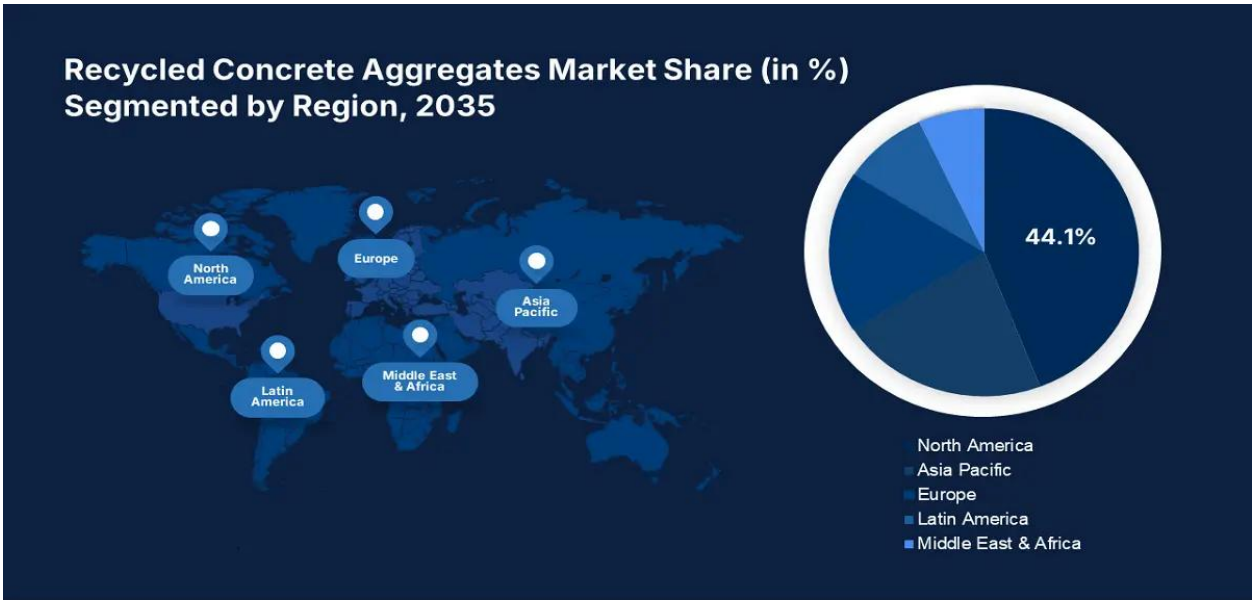
In Syria, the environmental benefits of RCA are not only theoretical but have been demonstrated in practice through post-conflict debris management and reconstruction efforts following the Syrian Civil War. Assessments and pilot projects led by the United Nations Environment Programme and the United Nations Development Programme show that RCA plays a critical role in diverting large volumes of demolition waste from informal dumping, conserving scarce natural aggregate resources, and reducing transport-related emissions when processing is performed close to demolition sites in cities such as Aleppo, Homs, and Damascus (UNEP 2024b; UNDP 2024b) .

These benefits are especially significant in Syria, where debris volumes are exceptionally high and access to virgin aggregate sources may be limited by damaged infrastructure or economic constraints (World Bank 2025). RCA, therefore, supports more resource-efficient and lower-carbon reconstruction, especially when combined with SCMs in new concrete production, as recommended in international reconstruction guidance. RCA production in Syria is not environmentally neutral. Field reports highlight that alkaline runoff, dust generation, noise, and residual solid wastes require active management. The technical measures needed to control these effects are well established globally, but the main challenge in Syria is consistent implementation under variable site conditions, evolving governance structures, and limited enforcement capacity. Donor-supported projects indicate that standard controls such as dust suppression, controlled drainage, and material segregation are feasible and effective when properly managed.

From a materials perspective, the Syrian experience reinforces the importance of characterizing RCA based on adhered mortar content, contamination levels, and interfacial bonding properties (Rashwani et al. 2023). UNEP technical guidance (UNEP 2023) emphasizes that high-quality recycling, in which processed concrete is reused as aggregate in new concrete, as the most valuable and sustainable pathway. However, because of variation in debris quality and limited testing capacity, much of the RCA in Syria is currently directed toward lower-grade applications such as road base, fill, and subgrade improvement. While these applications are beneficial, but they represent downcycling rather than full material circularity.

Looking forward, the key constraint in Syria is not a lack of technical knowledge but the need for stronger institutional and infrastructural support. Expanding laboratory testing capacity, establishing clear material specifications, and integrating RCA into public procurement frameworks are critical steps identified in UNDP and UNEP reconstruction strategies. Stronger supply chains and quality assurance systems would allow more RCA to re-enter the concrete production at higher value. The experience to date shows that concrete recycling can be implemented successfully in Syria without adverse environmental impact when managed properly. The lesson from UN-led initiatives and pilot programs confirms that the discipline required is not innovation, but consistency in applying established best practices. RCA is therefore a practical and scalable part of sustainable reconstruction in Syria, with the potential to move from an emergency response to a standard feature of the country’s long-term construction industry.

8. Recycled Concrete Aggregate: Economics, standards, challenges, and the road ahead



Source: www.researchnester.com

Recycled concrete aggregates offer significant economic advantages by reducing the costs of quarrying, transporting, and disposing of virgin aggregates. While RCAs are typically sold at a lower price per ton than newly quarried stone, their true value lies in avoided disposal fees and shorter haul distances, especially on urban demolition sites. The overall savings depend on project scale and quality requirements, since additional processing may be needed to remove contaminants or improve material consistency. Nonetheless, RCAs remain a cost-effective alternative for low-grade uses such as road base and bulk fill, while also reducing exposure to fluctuations in virgin material prices.

This chapter reviews the economic case for RCA use, along with the standards, best practices, and emerging technologies, for example, artificial intelligence, carbonation treatment, and performance-based design, that are expanding its potential.

8.1—Economic considerations

Recycled concrete aggregate is increasingly attractive from both an economic and environmental standpoint. It is typically 20–30% less expensive to purchase than natural aggregate and can deliver greater overall value once lower transport costs, avoided disposal fees, and reduced dependence on virgin materials are considered (Dacić et al. 2024; de Brito and Silva 2016). In some cases, producing coarse RCA has been estimated to be about 40% more cost-effective than sourcing natural aggregate (Tam et al.. 2023).

8.1.1 *Cost comparison with natural aggregates*

RCA's price advantage comes primarily from existing concrete rather than quarried stone. Because it is often sourced locally, it also benefits from shorter supply chains and lower haulage costs. At the project level, recycling concrete has been estimated to reduce total costs by 34–41% compared with demolition and replacement using virgin materials. This is a more useful measure than unit price alone because it reflects the combined effect of material cost, transport, and avoided disposal fees.

In Syria, these advantages are especially significant. The country has vast quantities of war-damaged concrete, which provides an abundant local feedstock. At the same time, fuel is expensive, infrastructure is damaged, landfill capacity is limited, and sanctions constrain supply chains. Under these conditions, RCA can reduce reconstruction costs, limit import dependence, and support more resilient material supply. Syria also has an opportunity to adopt performance-based RCA standards from the outset rather than relying on outdated specifications. Pilot projects using tools such as AI-based quality assessment and carbonation treatment could help build confidence in the material.

8.1.2 *Transportation and processing costs*

Transportation is one of RCA's most consistent economic advantages over natural aggregate. Quarried stone must be hauled from extraction sites that may be far from the point of use, which adds fuel, labor, vehicle wear, and emissions costs. RCA, by contrast, is usually generated close to where construction demand already exists, making it inherently local. On-site or near-site recycling is the most economical model. It eliminates both the outbound transport of demolition waste and the inbound delivery of virgin aggregate. For large urban demolition-rebuild projects, these logistics savings alone can justify mobile crushing equipment.

Processing costs depend on the crushing method, source cleanliness, and required gradation. Simple jaw crushing for road base or subbase is the least expensive option. By contrast, producing RCA suitable for structural concrete requires more screening, possible secondary crushing, and stricter quality control. In some high-performance applications, those processing costs can approach or even exceed the cost of virgin aggregate.

8.1.3 *Lifecycle cost analysis*

Lifecycle cost analysis is especially important in Syria because reconstruction will occur at a large scale and under tight budget constraints. For road base, subbase, fill, and lower-grade structural concrete, RCA often provides the most cost-effective solution. Its lower material cost does not necessarily come at the expense of service life, which is particularly important in a resource-constrained environment.

Carbonated RCA concrete can also offer environmental benefits. Mortars produced with 100% carbonated recycled aggregates can achieve CO_2 emission reductions of up to 36.75% compared to mixtures without recycled materials (Farinha et al. 2024). At industrial scale, carbonation treatment of RCA has been shown to achieve net positive carbon abatement of 21.42 kg CO_2 equivalent per ton of carbonated aggregate (Ang et al. 2024). More recent work in 2025 confirms that accelerated carbonation can reduce cement content by 10% while improving aggregate strength by over 70% (Hu et al. 2025). These findings make carbonated RCA particularly attractive for resource-constrained reconstruction environments like Syria.

8.1.4 *Market availability and demand*

RCA supply is not uniform. In dense urban areas with high demolition activity, supply can be abundant and reliable. In rural or rapidly developing areas, it may be limited or unavailable. This geographic variation means RCA is best treated as a local resource whose value depends on proximity to demolition activity and reconstruction demand.

Table 8.1.4: Cost comparison—RCA vs natural aggregate (summary of key parameters) (Sources: Lu 2024; Dacić et al. 2024).

Cost Parameter	Natural Aggregate	RCA	Notes
Purchase price (per ton)	Baseline	20–30% lower	Gap is larger where quarries are distant
Long-term production cost	Baseline	~40% lower	Varies by local economic policy
Transport cost	Higher (long haul from quarry)	Lower (local source)	Maximized by on-site recycling
Disposal / landfill avoided	n/a	USD 15–41/ton credit	Depends on local landfill levy
Overall project cost reduction	Baseline	34–41% lower	Reflects whole-project economics
CO_2 reduction (vs NAC)	Baseline	23–28% lower	Also influenced by recycling process emissions

RCA's economic case is strongest when it is used locally, matched to the right application, and supported by appropriate quality control. In Syria, where material scarcity and reconstruction urgency intersect, it is both a practical cost-saving measure and a strategic resource for rebuilding.

8.2. Standards and specifications

The standards landscape for RCA is more developed than many practitioners realize, but it remains still incomplete. The main gaps is between existing standards formally require and what RCA's natural variability demands in practice. Anyone specifying or producing RCA for regulated applications needs to understand the relevant frameworks, their scope, and their limitations.

8.2.1 *ASTM international*

ASTM C33 is the principal United States standard for concrete aggregates and is widely referenced internationally. It covers grading and quality requirements for both natural and recycled aggregates. Recycled concrete can be used as either fine or coarse aggregate provided it meets the quality and gradation criteria in the standard. However, ASTM C33 does not address RCA-specific issues such as higher water absorption, inconsistent mortar content, or contamination risk. For that reason, compliance with ASTM C33 is necessary but not sufficient; RCA-specific evaluation and adjustments are also required.

Relevant companion standards include ASTM C131 for Los Angeles abrasion test, ASTM C127 and C128 for specific gravity and absorption, ASTM C157 for drying shrinkage. For pavement applications, the FHWA guidance references ASTM C33 and AASHTO M 80, and requires RCA used in concrete paving to be free of harmful components, with over 90% cement paste and aggregate, and asphalt content below 1% (FHWA T 5040.37).

8.2.2 *AASHTO specifications*

AASHTO publishes a parallel framework to ASTM for highway construction materials. AASHTO M 80 governs coarse aggregate for hydraulic cement concrete and permits crushed concrete aggregates without specifically addressing RCA. AASHTO MP 16 is more directly applicable because it classifies RCA for use as coarse aggregate in hydraulic cement concrete by exposure severity: Class A for severe exposure, Class B for moderate exposure, and Class C for minimal exposure.

Other useful AASHTO standards include R 80 for alkali-silica reactivity testing, AASHTO T 336 for coefficient of thermal expansion, and AASHTO M 319 for alternative soundness evaluation methods. These are particularly important for RCA because residual reactive silica, thermal behavior, and misleading sulfate soundness results can all affect performance.

8.2.3 *European standards*

In Europe, the main standards are EN 13242 for aggregates used in unbound and hydraulically bound materials and EN 12620 for aggregates used in concrete. EN 12620 provides the framework for classifying and specifying recycled aggregates, while national annexes allow member states to apply stricter or more flexible requirements.

The European approach places greater emphasis on source classification than the U.S. framework. Materials are categorized by composition, including the proportion of concrete, masonry, bituminous material, and other constituents. Higher concrete content generally allows higher-grade use, reflecting the fact that RCA quality depends heavily on the original source material.

8.2.4 *Syrian standard*

A dedicated RCA standard does not currently exist in Syria. Instead, engineers must work within the general Syrian Arab Code, a framework not designed to address RCA's unique properties. These include higher water absorption, variable mortar content, and contamination risks. As reconstruction demands rise, driven by scarce natural aggregates and abundant war-damaged concrete, this gap generates uncertainty for engineering decisions. It also increases liability for material producers and heightens the risk of either discarding serviceable material or incorporating unsuitable material.

A Syrian RCA standard, adapted from ASTM, AASHTO, or EN, but calibrated to local materials and exposure conditions, would provide clear quality classes, testing protocols, and application limits. Such a standard would reduce project costs, enable responsible use of local debris, give engineers the confidence to specify RCA where it is technically appropriate, and help rebuild the country more sustainably.

8.3—Challenges and limitations

Acknowledging the real challenges faced by RCA is more useful than minimizing them. Several of the barriers are technical constraints, while others are primarily perception-based or structural. Distinguishing between them matters for developing effective responses. The variability in RCA quality was discussed in Section 4.4. Other challenges and limitations are addressed below.

8.3.1 *Higher water absorption*

As established in Section 4.1.2, RCA exhibits substantially higher water absorption than natural aggregate—typically 3–10% compared to 0.5–4% for virgin materials. If not properly accounted for in mixture design, this can reduce workability and lead to unintended strength loss. These challenges are manageable but require batch-specific testing and careful water adjustment (Tam et al. 2006); see Chapter 5 for detailed mixture design guidance.

8.3.2 *Durability concerns*

As discussed in Section 4.1.3, the residual mortar on RCA particles makes concrete more porous, which can increase the penetration of chlorides, sulfates, and carbon dioxide. In mild exposure conditions, this may not be a major issue, but in aggressive environments it requires deliberate design measures. For Syria, the main concerns include coastal structures in Latakia and Tartus, buried infrastructure in sulfate-bearing soils, and bridge decks exposed to de-icing salts in mountainous areas.

Durability can be improved through lower water-to-cement ratios, supplementary cementitious materials, additional concrete cover, and selection of the appropriate RCA quality class for the expected exposure (Ozbakkaloglu et al. 2018). In countri8es without formal RCA standards, durability concerns often lead to unnecessary rejection of recycled material, even when it could perform well. Bridging the gap between research and practice through standards and training would help Syria use RCA more safely and effectively.

8.3.3 *Lack of awareness and acceptance*

The most significant barrier to RCA adoption in Syria is not technical but informational and awareness. And this barrier operates at multiple levels. Structural engineers who have never worked with RCA tend to apply overly conservative safety margins or simply default to natural aggregate to avoid the extra design considerations. Clients commissioning new buildings or infrastructure are rarely equipped to evaluate RCA's technical case. They rely entirely on their engineers' default choices. Meanwhile, outdated procurement specifications for natural aggregate persist unchanged.

For Syria, where reconstruction is urgent and demolition debris is everywhere, this awareness gap has real costs. Many engineers trained before RCA became a serious option may lack confidence in recycled materials. Government procurement documents drafted before the war rarely mention recycled aggregates. In a reconstruction environment shaped by damaged infrastructure and tight budgets, there is little time for trial-and-error learning.

The solution lies in education and demonstration. Webinars, technical bulletins, case studies, and formal training programs all help shift practitioner familiarity. For Syria, targeted efforts, for example, workshops for Syrian engineers, model procurement language for government contracts, and pilot demonstration projects using local debris, could accelerate this learning curve. The challenge is that these outreach mechanisms work slowly, while Syria's reconstruction needs are urgent. A national standard for RCA would help bridge this gap by giving engineers and clients clear, credible guidance they can trust and apply immediately (Tam et al. 2008), refer to Section 8.2.

8.3.4 *Regulatory and specification barriers*

Even when technical knowledge and willingness exist among Syrian engineers, regulatory barriers can still prevent RCA use. Specifications that limit aggregate absorption to 2%, for example, may be reasonable for virgin stone but exclude most RCA, which typically absorbs 3% to 8% water. Similarly, requiring all aggregates to meet the same abrasion loss limits regardless of application disqualifies RCA in contexts where its abrasion resistance is perfectly adequate, such as low-traffic road bases or non-structural fill. Prescriptive specifications that list approved materials without explicitly including RCA force contractors to seek case-by-case approval from authorities, adding delay and cost.

The most effective reform is to shift toward performance-based specifications. These focus on required outcomes such as strength, permeability, and durability rather than on material origin. This approach allows RCA to be used where it performs well without requiring special exemptions. For Syria, performance-based standards would remove a major barrier and allow war-damaged concrete to be used more responsibly as a reconstruction resource (Behera 2014).

8.4—Best practices and recommendations

Successfully using RCA in Syria requires attention to the full process chain, from debris sorting and crushing to mixture design, policy support, industry adoption, and continued research. Technical performance depends not only on the material itself, but also on how consistently it is produced, specified, and applied.

8.4.1 *Processing and quality control*

Consistent RCA quality starts at the source. Selective demolition, where concrete is separated from brick, timber, plasterboard, and asphalt before or during removal, is the most effective way to reduce contamination and improve feedstock quality. In Syria, war-damaged buildings are of mixed construction types, this approach can reduce rejected batches and improve the reliability of downstream processing (Beattie et al. 2022).

During processing, jaw crushers are preferred for primary reduction because they handle large concrete fragments efficiently and generate fewer fine particles than cone or impact crushers. Screening should follow crushing to remove oversized particles, light contaminants, and materials that require secondary crushing. Air separation can also remove paper, wood, and plastic that screening alone may miss. Separate stockpiles should be maintained for different RCA gradations and clearly labeled by source to preserve traceability (Gebremariam et al. 2025).

Testing is essential for any RCA intended for structural use. At a minimum, each lot should be checked for density, water absorption (see Section 4.1.2), gradation, and deleterious materials. Because RCA quality can vary significantly between batches, testing should begin before the first load is used and continue throughout the project. Without routine verification, engineers cannot specify the material with confidence , and contractors face greater performance risk (Tam et al. 2006).

8.4.2 *Mixture design adjustments*

RCA concrete must be designed differently from concrete made with natural aggregate. The aggregate should be characterized before batching, and mixture designs should include water corrections or pre-wetting to account for higher absorption. Lower water-to-cement ratios are usually necessary, and supplementary cementitious materials should be considered standard rather than optional. Trial batching should then confirm that the design produces the required fresh and hardened properties (Kryeziu et a. 2023; Poon et al. 2004).

For partial replacement, research generally supports replacing 30–50% of the coarse aggregate with RCA. This range usually offers the practical balance of strength, durability, and workability. Fine RCA is typically limited to about 30% of the fine aggregate fraction. These values should be treated as starting points, not fixed limits, because the appropriate ratio depends on source quality and project requirements (McGinnis et al. 2017).

8.4.3 *Policy and regulatory support*

The most effective policy tools are those that change the economics of RCA use. Landfill taxes, aggregate extraction taxes, recycled content mandates, green building incentives, and Buy Clean requirements all make recycled material more competitive. For Syria, where budgets are tight and natural aggregates are becoming scarcer, recycled content mandates in public reconstruction projects would be especially useful. They would create reliable demand and help build local RCA processing capacity (Daiber 2022).

Performance-based specifications are equally important. By focusing on strength, permeability, durability, and other measurable outcomes rather than material origin, these specifications allow RCA to compete on performance instead of exemption. This approach reduces unnecessary exclusions and case-by-case approvals. It would also give Syrian engineers greater flexibility while still maintaining quality through testing and performance criteria (Silva et al. 2019).

8.4.4 *Industry adoption*

RCA adoption increases when practitioners can see successful applications in practice. Early projects should therefore be carefully designed, documented, and communicated through case studies, technical bulletins, and agency reports (Oikonomou 2005). These materials help reduce uncertainty and demonstrate that RCA can perform reliably when properly processed and specified.

For Syria, demonstration projects in cities such as Aleppo, Homs, or Damascus would be especially useful. They would help engineers, contractors, and clients build confidence in the material. Over time, consistent demand would also encourage supply-chain development, since contractors are unlikely to invest in processing capacity without reliable buyers, and specifiers are unlikely to require RCA without dependable supply.

8.4.5 *Research and development needs*

Several research gaps still limit wider RCA adoption. Performance-based mixture design models would reduce the need for repeated trial batching and make RCA easier to specify at scale. Long-term field data are also needed, especially for Syria's varied exposure conditions, including coastal humidity, sulfate-bearing soils, and mountain routes where de-icing salts may be used.

Treatment technologies such as carbonation, slurry coating, and acid washing also deserve further development. These methods can improve durability and reduce absorption, but they are not yet widely used at industrial scale. For Syria, pilot-scale deployment could help transform lower-grade demolition debris into higher-value aggregate.

8.4.6 *Advanced treatment technologies*

RCA production still relies primarily on crushing, screening, and sorting, but residual mortar remains a major limitation. Treatment methods that remove or densify that mortar can significantly improve performance. Carbonation treatment is the most advanced option and has shown strong laboratory results, including improved strength, lower water absorption, and potential carbon-sequestration benefits (Xuan et al. 2017).

Other approaches include acid washing, cement slurry coating, and bio-deposition. Each has advantages and trade-offs, but none is yet widely commercialized. For Syria, the immediate priority is likely to be reliable mechanical processing and quality control. As the sector matures, these treatments could expand the range of RCA applications.

8.5—Emerging Technologies: AI and Advanced Applications

Artificial intelligence is beginning to improve waste sorting, quality control, and mixture design. Computer vision systems can identify and classify demolition materials more consistently than manual sorting (Martin et al. 2022), and machine learning can help predict concrete performance from RCA properties (Han et al. 2020). These tools could reduce trial batching and improve feedstock consistency.

For Syria, AI may not be the first solution, but it could become useful as RCA production becomes more formalized. In a post-conflict setting where skilled labor and laboratory capacity may be limited, automated quality assessment could eventually provide a practical advantage.

8.5.1 *Moving RCA beyond low-grade applications*

A major opportunity lies in moving RCA beyond low-grade uses. With advanced treatment and better mixture design, RCA concrete can approach the performance of natural aggregate concrete in some applications (Xuan et al. 2017). If these laboratory gains can be translated into practice, RCA could be used in structural concrete, bridges, and other demanding infrastructure.

For Syria, this would be a major step toward true circularity. Demolished concrete would re-enter the supply chain at a higher value instead of being downgraded to fill or base material. That shift would be both economically and environmentally significant.

8.5.2 *Integrating RCA into a broader sustainable construction framework*

RCA should also be integrated into a broader sustainable construction strategy. Building information modelling can help track material composition for future reuse. Design for deconstruction can make future recycling easier. Life cycle assessment tools can help designers compare cost, performance, and environmental impact in real time (Akbarnezhad and Xiao 2017).

Taken together, these measures would move RCA from being a fallback material to being a planned part of the construction system. For Syria, this is a realistic long-term goal. With the right policy support, technical guidance, and pilot projects, RCA can become a core element of reconstruction rather than just a waste-management response.

9—Conclusions: The path forward for RCA in Syria

The economic advantages of RCA are well established. Typical material costs are 20–30% below those of natural aggregate (Tam et al. 2008), and whole-project savings increase further when transport, disposal, and regulatory costs are accounted for (FHWA 2022). It also requires less energy than quarrying and processing virgin materials. In Syria, where natural aggregates are becoming more expensive and demolition debris is abundant, RCA is not only a sustainable option but also a practical economic necessity.

The standards framework is usable, but it is still incomplete. Existing standards were designed primarily for natural aggregate and do not fully reflect RCA's variability (ACI PRC-555). Even so, research shows that replacing up to 30% of coarse aggregate with RCA can maintain acceptable performance, and well-designed RCA concrete can achieve roughly 85–95% of the strength of conventional concrete (Etxeberria et al. 2007; Fathifazl et al. 2009). For Syria, the immediate priority is to adapt an established international framework, such as ASTM, AASHTO, or EN, while building local testing and enforcement capacity.

Material quality must be managed carefully. High replacement levels can reduce strength, and poor grading or inadequate mixing can lead to inconsistent performance. Supplementary cementitious materials may be needed to meet strength and durability requirements. In Syria, where seismic risk is relevant in many areas, RCA should be specified with attention to structural demands and exposure conditions. These are not reasons to avoid RCA, but reasons to apply it with proper quality control.

The main barriers are institutional rather than technical. Specification inertia, limited familiarity among engineers, and inconsistent quality assurance across the supply chain remain the biggest obstacles. Addressing them will require training for engineers and contractors, well-documented pilot projects, policy support through recycled-content requirements, and investment in local processing capacity. A national RCA standard would give the sector clearer direction and reduce uncertainty.

Future potential is significant. Advances in carbonation treatment, AI-assisted sorting, and performance-based design are steadily improving RCA quality and expanding its range of applications (FHWA 2022). As these methods mature, RCA could approach parity with natural aggregate in an increasing number of uses. That would make it less a substitute material and more a preferred option for certain applications.

For Syria, the path forward is clear:

(a) Adopt a formal RCA standard adapted from ASTM, AASHTO, or EN frameworks.

(b) Require recycled content in publicly funded reconstruction projects.

(c) Establish pilot projects with careful monitoring and documentation.

(d) Invest in local processing, testing, and quality-control capacity.

(e) Train engineers and contractors in RCA design and specification.

(f) Track long-term performance to build a local evidence base.

Syria has an unusual opportunity to turn war debris into a durable reconstruction asset. With the right standards, training, and policy support, RCA can help the country rebuild more affordably, reduce landfill pressure, conserve natural resources, and advance circular construction practice. In that sense, RCA is not just an environmental choice; it is one of the most practical ways to support long-term resilience and recovery.

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