Open Access

Recent Progress in Materials

LIDSEN Publishing Inc.

Review

Recycled Concrete Aggregates: Production, Properties of RCA and RCA-Based Concrete, and Economic Considerations

Shahriar Abubakri [*], Gilson R. Lomboy, Douglas B. Cleary

Center for Research and Education in Advanced Transportation Engineering Systems, and Department of Civil and Environmental Engineering, Rowan University, 201 Mullica Hill Road, Glassboro, NJ 08028, USA; E-Mails: abubakri@rowan.edu; lomboy@rowan.edu; cleary@rowan.edu

* **Correspondence:** Shahriar Abubakri; E-Mail: abubakri@rowan.edu

Academic Editor: Tahseen D. Saadoon

Special Issue: Application of Recycled Materials in Civil and Environmental Engineering

Recent Progress in Materials
2026, volume 8, issue 2
doi:10.21926/rpm.2602004

Received: February 10, 2026
Accepted: June 07, 2026
Published: June 15, 2026

Abstract

The use of recycled concrete aggregate (RCA) offers a sustainable alternative to traditional virgin aggregates in concrete production, helping mitigate the environmental impacts associated with mining and construction waste disposal. RCA is characterized by the presence of attached mortar from previous concrete applications, which significantly influences the mechanical properties of the aggregates, as well as mix design and the overall performance of new concrete incorporating these recycled materials. This paper provides a comprehensive review of various aspects related to RCA, encompassing its production, inherent properties, and economic considerations. It provides a detailed analysis of specific attributes of recycled concrete aggregates such as shape, particle density, water absorption, abrasion resistance, and mortar content, and reveals their implications on mix design processes. Furthermore, the paper critically examines and discusses both the fresh and hardened properties of concrete utilizing recycled concrete aggregate.

© 2026 by the author. This is an open access article distributed under the conditions of the Creative Commons by Attribution License, which permits unrestricted use, distribution, and reproduction in any medium or format, provided the original work is correctly cited.

Keywords
Recycled concrete aggregate; construction waste; economic consideration; properties of RCA; classifications of RCA

1. Introduction

The global consumption of construction aggregates is immense, surpassing 26 billion metric tons annually, with substantial environmental consequences [1-3]. In the USA alone, around two billion tons of aggregates are produced each year, raising concerns about the environmental effects and the sustainability of future sources [4, 5]. Although concrete is known for its durability, various factors necessitate the demolition of concrete structures, including irreparable damage, modifications, or the end of their useful life [6-8]. Consequently, large volumes of construction demolition waste are generated annually, highlighting the environmental and economic significance of recycling strategies and recycled concrete aggregates [9].

Recycling demolished concrete as a replacement for virgin aggregates provides an alternative aggregate supply while reducing waste and preserving landfill space, which is crucial in areas reliant on imported aggregates. Dimitriou et al. [10] highlight that producing recycled concrete aggregate (RCA) may involve a more complicated process than simple crushing, yet it can still be cost-effective, sometimes halving the expense compared to importing virgin aggregate. However, the cost difference between recycled and virgin aggregates depends on project-specific factors such as scope, site logistics, and local market [11]. Snyder et al. [11] listed multiple cost-saving benefits of recycling aggregates, including reclaiming materials value, using less time and fuel, making production more efficient, lowering transportation costs, and improving quality control. Moreover, as the availability of natural aggregates decreases and demand rises, prices are likely to increase [1]. These advantages have led to numerous international studies on using construction waste materials as a replacement for Natural Aggregates (NA) in concrete.

Policies regarding the use of RCA and Recycled Aggregate (RA) vary from country to country. In the United Kingdom, RCA is defined as aggregates derived from concrete-based materials consisting of at least 95% (by weight) crushed concrete, whereas RA originates from mixed waste containing less than 5% crushed concrete [12]. According to the British standard BS 8500-2:201 [13], the use of RA is restricted to specific applications such as road surfaces and underpinning works, and it is limited to concrete with a compressive strength of C16/20 due to its diverse properties and origins. The standard also allows up to 20% RCA (by weight) as a partial replacement for NA in concrete with strengths up to C40/50 (40 to 50 MPa).

Despite the potential benefits of recycling demolished construction materials, such as reduced new materials usage and the reclamation of waste value, the construction industry often hesitates to adopt these practices due to concerns about the unpredictable performance of materials with inconsistent properties [14]. For instance, in large-scale projects, RCA typically comes from crushed concrete from different structures, resulting in a broad range of material qualities. Additionally, there is a widespread belief that concrete made with RCA is of lower quality. The lack of technical data, mix specifications, and quality control or assurance guidelines for processing RCA worsens these concerns. Nonetheless, recycled concrete aggregates are increasingly recognized for their potential to promote sustainability in construction. Number of review papers [1, 4, 15-18] have explored specific aspects of RCA, including treatment, properties, and concrete performances. However, a comprehensive review that covers the full scope of recycling concrete aggregate is still needed. This paper aims to fill that gap by providing an in-depth review of the complex factors involved in reusing recycled concrete aggregates, from their life cycle to economic considerations. Engineers and researchers seeking an extensive understanding of challenges and opportunities associated with RCA may find this paper particularly valuable.

The review was prepared by searching relevant journal articles, conference papers, technical papers, and reports, and by the expertise of the authors in the field. Literature selection was conducted using major scientific databases (e.g., Scopus, Web of Science, and Google Scholar) with keywords related to the properties and durability of RCA. Studies were selected based on their relevance to the scope of the review, with priority given to peer-reviewed articles, widely cited papers, and standards to ensure up-to-date coverage. In addition, technical reports and standards were included where they provided fundamental insights or practical guidelines not fully addressed in the academic literature. Studies focusing on unrelated recycled materials or lacking sufficient experimental or analytical detail were excluded.

2. Demolition of Concrete Structures

The popularity of concrete is due to the fact that it is cheap and durable, and its raw materials are available worldwide for construction purposes. However, concrete structures require regular monitoring and maintenance throughout their service life, and eventual demolition at the end of their service life.

The demolition of concrete structures produces composite waste which may contain various materials such as brick, tiles, ceramic, concrete, plastic, metal, wood, soils, stones, insulation, and gypsum-based materials [19, 20] as shown in Figure 1. The treatment and processing of construction and demolition waste into RCA are done in both stationary and mobile facilities [21]. Stationary facilities are plants authorized to recycle construction waste that are based at a fixed location, use heavy, fixed equipment, and do not conduct off-site operations. On the other hand, mobile facilities bring recycling machinery, such as screens, crushers, and magnetic and vibratory separators, directly to the site for on-site materials recycling [9]. While stationary plants are more common due to their greater capacity and efficiency in producing natural aggregate at lower processing costs, mobile plants mitigate transportation costs. This advantage is especially attractive in densely populated regions where the proximity of demand and supply significantly affects overall costs.

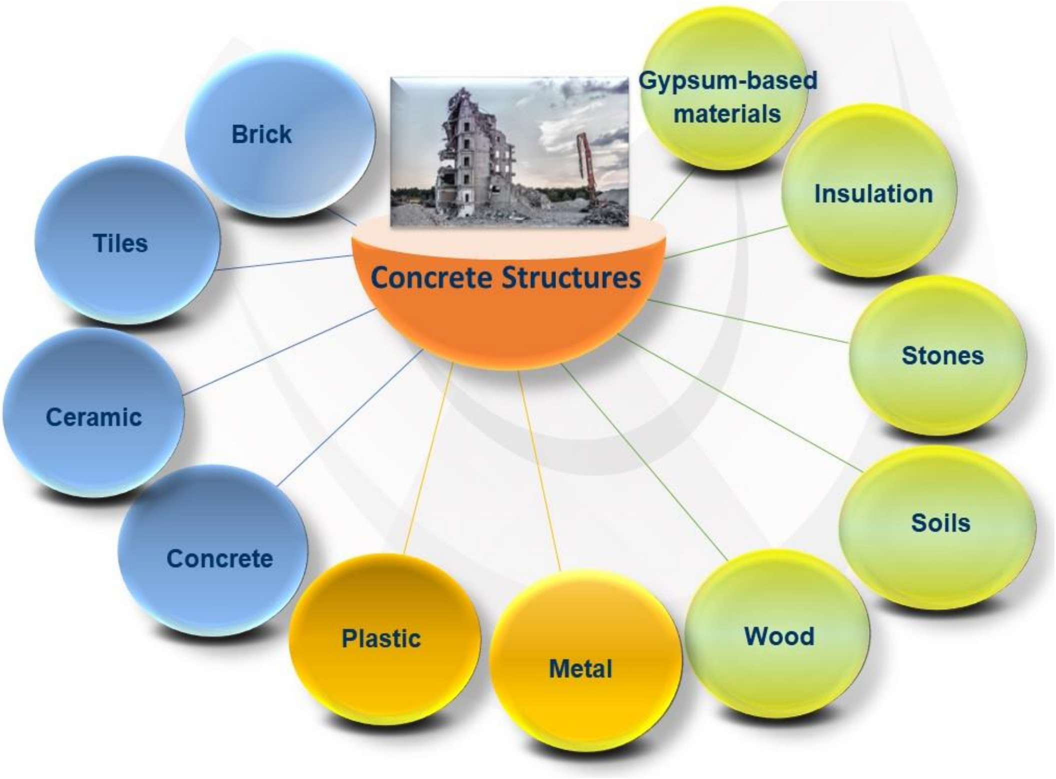

Figure 1 Concrete structures after demolishing.

Both facilities process aggregates from construction and demolition waste using a process that includes separation, crushing, screening, metal removal, and the removal of impurities such as wood and plastic. Initially, various pieces of machinery crush and reduce the material size, often in multiple stages, to achieve the desired grading. Recycling operations might also involve repeated screenings to remove wood and plastic, magnetic separation for metals, and decontamination to ensure purity. Typically, aggregates produced in the early stages are considered low quality, whereas those from the final stages are regarded as medium to high quality.

2.1 Methods to Demolish Concrete Structures

Concrete structures can be demolished through various methods, ranging from mechanical machines to chemical processes [21-23]. Among the most common demolition techniques are pneumatic and hydraulic breaking, pressure bursting, dismantling, the ball and crane methods, and implosion as shown in Figure 2.

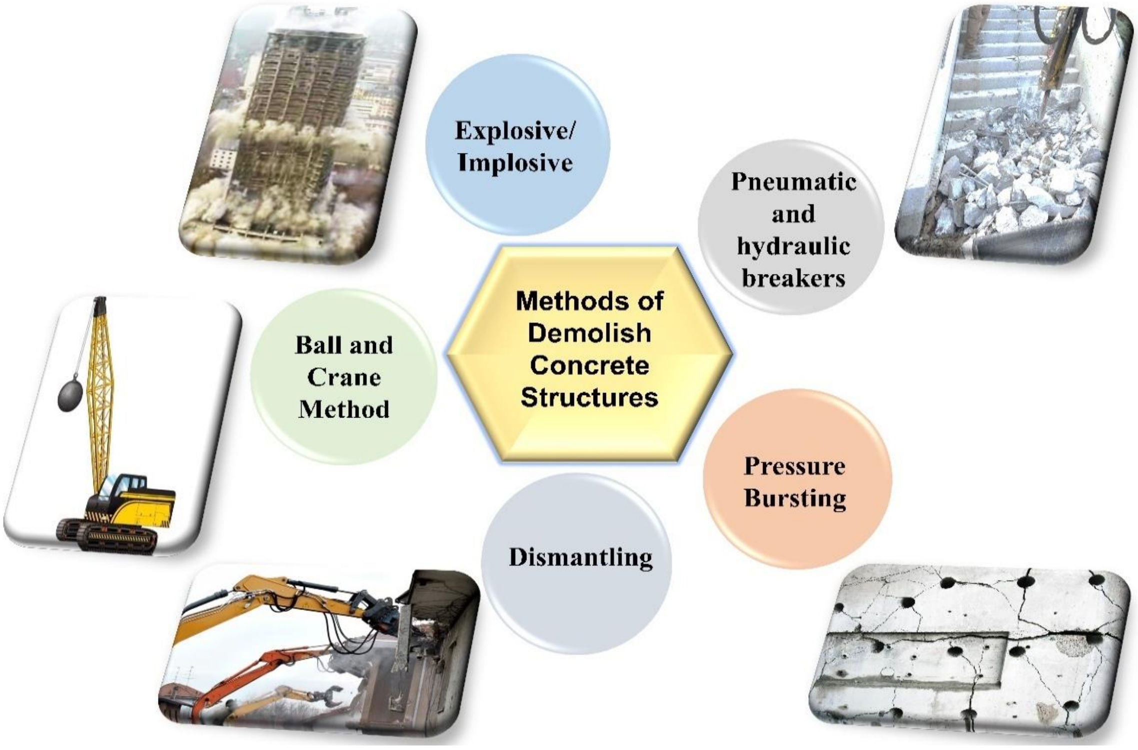

Figure 2 Typical methods of concrete structure demolition.

2.1.1 Pneumatic and Hydraulic Breakers

This is a commonly employed method for demolishing pavements, bridge decks, and foundations. The complexity of this method is influenced by factors including the strength of the concrete, the size of the hammer, the working conditions, and the amount of steel reinforcement in the concrete.

2.1.2 Pressure Bursting

Pressure bursting involves applying high hydraulic pressure or an expansive chemical slurry to predetermined patterns to split concrete. When using a chemical slurry, known as soundless chemical demolition agents (SCDAs) [24], powdery materials containing substances such as lime, silica, ferrous oxide, and calcium fluoride are used to regulate the rate of slurry hydration. Upon contact with water, the slurry expands and generates pressure within a time frame ranging from as quickly as 15 minutes to as long as 24 hours [25]. This method offers a dust-free, controlled, and relatively quiet approach to demolishing and removing concrete structures.

2.1.3 Dismantling

The dismantling process is an efficient method in which sections of the structure, such as cantilevered elements, balconies, slabs, or walls, are cut into smaller components using tools such as saws, thermal lances, or water-jet techniques. Rathi and Khandve [26] outlined the general sequence of dismantling as follows: first, removing exterior walls, then removing any structures and dead loads supported by cantilevers, and finally, gradually breaking down from the outer edge of the cantilevered floor inward toward the supporting beams. This method is designed to minimize the impact on surrounding structures.

2.1.4 Ball and Crane Method

The ball and crane method is another technique for demolishing structures where a heavy ball (weighing up to about 6 tons) is swung or dropped into the structure. This method is used to demolish concrete structures where their height is greater than 5 stories and normal excavator types of machinery are not sufficient [22]. This method demands great skill from the operator, and the size of the crane and working room limits the maximum height of the building that can be demolished. In addition, the process causes considerable dust, vibration, and noise [27].

2.1.5 Explosive/Implosive

If a large volume of concrete needs to be demolished or removed, explosive materials (military or commercial explosives) [21] may be inserted in a series of predetermined boreholes to blast and break the structure into smaller pieces. It is an effective method, especially for large buildings, where exploding support columns and a few upper stories cause the whole structure to collapse. This is a flexible and versatile method; however, there should be careful consideration for the air blast and vibration that may cause damage to the surrounding structure, and most importantly, the safety during the process.

Implosion involves weakening or removing critical supports of a structure so that the building can no longer withstand the force of gravity and collapses under its weight. This method is particularly desirable for tall buildings in urban areas, especially when surrounded by numerous structures that must be preserved [28], and where other demolition methods may not be feasible. A well-designed implosion causes the structure to collapse inward, toward the center of the building and within the protected area [26].

The demolished concrete structures can then be recycled and used to produce aggregate for new concrete structures. This can be achieved by crushing demolished concrete structures to smaller sizes similar to aggregate, so it can ideally fully or at least partially replace virgin aggregates.

2.2 Crushing Process and Gradation

A concrete recycling plant crushes concrete through primary and secondary crushers. Initially, the size of the concrete is reduced to 8-10 cm (3-4 in) by primary crushers, and then secondary crushers further reduce the materials to the desired maximum coarse aggregate size. Jaw, cone, and impact crusher designs are used in concrete recycling plants [29]. The selection of crushers relies on material size, operating cost, the desired end product, and environmental considerations [30, 31]. Jaw crushers tend to leave higher levels of cement paste adhered to recycled aggregates, while impact cone crushers are more effective in removing adhered hardened cement paste [32]. Different crushing processes remove different amounts of mortar from the original aggregate particles, and they produce different RCA gradations. Gradation describes the particle size distribution of the aggregate, and its maximum size is limited by equipment capability, dimensions of construction members, clearance between reinforcing steel, and layer thickness [33]. The maximum aggregate size is referred to as the smallest size sieve that 100% of the aggregates pass through. The degree of mortar removal and gradation also depends on the properties of the natural aggregates used in concrete. Recycled aggregates can be specified to the same gradation as virgin aggregates [34]. The desired gradation of aggregates for both virgin and recycled can be produced similarly by programming crushing equipment and using proper screening [35].

2.3 Economic Viability

Despite available comprehensive literature related to the use of recycled concrete aggregate, there are a very limited number of studies related to the economic and environmental life cycle impacts of replacing RAs with NAs [36, 37]. Gangolells et al. [38] surveyed 74 Spanish construction companies based in Catalonia and found that most of the opportunities identified by the construction firms are within the scope of the government and related to the combined system of bonuses and penalties.

Duran et al. [39] developed a model for assessing the economic viability of construction and demolition waste. They identified several factors to influence the economic feasibility of recycled concrete aggregates. The decision of which aggregate to use (RCA or NA) was based on the following expression [39]:

$$Q_p + T_q > E_{ru} + RC_p + T_{ru} \tag{1}$$

Where Q_p is the price per ton of NA at the quarry gate; T_q is the cost of transportation from the quarry to the site (per ton); E_{ru} refers to any additional cost per ton created by using the recycled concrete (for example, the addition of cement content); RC_p the price per ton of recycled concrete at the recycling center and T_{ru} is the cost per ton of transportation from recycling center to the site. Martinez-Large et al., [40] used the above model to study the economic viability of concrete with ranges of compressive strength under different scenarios. They concluded that the use of recycled aggregates instead of natural aggregate may increase the cost under certain conditions, particularly when additional cement or processing is required to meet performance criteria. Therefore, they suggested that the government should take necessary measures to facilitate the use of recycled concrete aggregates. This can be achieved by imposing additional penalties and taxes for landfilling [41], increasing the price for NA, or subsidizing recycled aggregates. The Netherlands is reported to be the country with the highest recovery rate of construction demolition waste due to long-standing landfill restrictions [42]. The introduction of the landfill tax in 1995 and the landfill ban in 1997 in the Netherlands contributed to the reduction of landfilling of concrete demolition waste significantly [43].

Based on Equation (1) and literature, the economic viability of RCA is strongly influenced by processing, transportation, and avoided disposal costs. While processing operations such as crushing and screening are generally comparable to those used for natural aggregates production, their contribution to the overall cost is often secondary relative to other factors [42, 44, 45]. Instead, transportation cost is consistently identified as a dominant parameter, as it is highly sensitive to the relative distance between the construction site, quarry, and recycling facility [39, 40, 45]. Additional cost may arise from mix design modifications, such as increased cement content or the use of admixtures to achieve comparable mechanical performance when RCA is used [9, 40]. However, these potential increases are often offset by the economic benefits associated with avoided landfill disposal, which eliminates tipping fees and reduces environmental burden, thereby improving the competitiveness of RCA [41, 42, 45]. As shown in Table 1, the economic advantages of RCA are therefore not derived solely from construction cost, but rather from the combined effects of transportation logistics and landfill cost avoidance. At the project level, these benefits become more pronounced when recycling is performed on-site, where reduced hauling distances and disposal requirements can significantly decrease total project costs while generating reusable aggregate. Consequently, transportation distance and local landfill conditions are identified as dominant parameters governing the economic feasibility of RCA, consistent with Equation (1).

Table 1 Economic aspects influencing RCA feasibility.

Cost aspect	Economic Implication	References
Processing (Crushing and screening)	Comparable to NA production	[42, 44, 45]
Transportation cost	Dominant, but highly variable, strongly depends on haul distance (quarry vs recycling plant)	[39, 40, 45]
Additional material cost	May increase cost when extra cement/admixtures are required to match performance	[9, 40]
Landfill cost avoidance	Major economic benefit, avoiding tipping fees improves RCA competitiveness	[41, 42, 45]

In addition to these conventional economic considerations, recent studies incorporated multi-objective optimization frameworks that simultaneously evaluate mechanical performance, cost, and environmental impact in sustainable concrete design [46, 47]. These approaches extend traditional cost-based analyses by integrating parameters such as CO_2 emissions and material efficiency into the decision-making process [46]. A notable example in sustainable cementitious systems involves the application of machine learning-assisted mix design to optimize trade-offs between compressive strength, cost, and carbon emissions. This is demonstrated for waste glass powder concrete using predictive modeling and the NSGA-II multi-objective optimization algorithm [48]. Although developed for a glass powder system rather than recycled aggregate concrete, the methodological framework is directly transferable to RCA-based mixes, where variability in material properties and the need for mix adjustments introduce comparable complexity [47, 49]. Data-driven, multi-objective strategies, combining ML-based strength prediction with simultaneous optimization of CO_2 emissions and cost, have demonstrated practical applicability in RCA mix design process [46, 49], providing a promising framework for selecting optimal RCA-based mixtures and enabling more balanced and performance-oriented decision-making compared to conventional single-parameter economic evaluations.

3. Properties of Recycled Concrete Aggregate

Coarse aggregate comprises about 60-75% of the total volume of the concrete [15]; therefore, the properties of the aggregate significantly affect the fresh and hardened properties of concrete, including the long-term durability properties. Completely or partially replacing virgin aggregates with recycled concrete aggregates will affect the fresh and hardened properties of concrete. In general, recycled aggregates are not universally classified worldwide, and some developed countries limit the design to partial replacement with recycled aggregates in concrete for structural applications due to the safety considerations related to the lower strength or durability concerns.

However, recently, many countries have introduced classification systems for recycled aggregate to be used for new concrete structures, including pavements, foundations, roadways, etc., to encourage engineers to use the material [50, 51].

Recycled concrete aggregates are different from virgin aggregates mainly due to the existence of adhered mortar content (AMC). The adhered mortar significantly affects the mechanical and durability properties of RCA and is generally considered the primary factor governing its performance [52]. However, other parameters, including the quality of the parent concrete, crushing method, and moisture condition of the aggregates, also play important roles and may become dominant depending on the specific property under consideration. For example, adhered mortar primarily controls density and water absorption, while the quality of the original concrete and crushing process can significantly influence strength-related properties and particle shape. Similarly, the moisture condition of RCA strongly affects fresh properties such as workability. Due to the importance of the AMC, this property is further discussed in Section 3.5.

Some typical properties of natural aggregate and RCA are presented in Table 2 [53, 54]. Some of these properties are reviewed in more detail in the following sections. To better distinguish the dominant influencing mechanism, Table 2 also summarizes the primary and secondary factors governing key fresh and hardened properties of RCA-based concrete.

Table 2 Typical properties of virgin aggregate (NA), recycled concrete aggregate (RCA), and key factors including RCA behavior.

Property	**NA**	**RCA**	**Dominant factors influencing RCA Properties** [a]		
			Primary	Secondary	Practical note & key references
Shape and texture	smooth to crushed	Angular with rough surface	AMC content, crushing method	Parent concrete grade	Impact crushing produces more spherical particles, jaw crushing produces more fines [55]
Absorption (%)	0.8-3.7	3.7-8.7	AMC content, AMC porosity/ITZ quality	Parent concrete grade Crushing-induced micro-cracks	Most AMC-sensitive property; 3-9× higher than NA [56, 57]
specific gravity	2.4-2.9	2.1-2.4	AMC content Parent concrete grade	Moisture condition, Crushing method	Porous adhered mortar lowers density [56, 57]
LA abrasion Loss (%)	15-30	20-45	Parent concrete grade AMC content	Crushing method	Weak adhered mortar increases abrasion loss [58, 59]

Sodium Sulfate Soundness Loss (%)	7-21	18-59	AMC porosity & connectivity Parent concrete quality	Moisture condition Crushing-induced micro-cracks	Porous AMC increases salt crystallization damage [53]
Magnesium Sulfate Soundness Loss (%)	4-7	1-9	Parent concrete quality	AMC content	High-quality parent concrete can approach NA performance [53]
Chloride content (kg/m^3)	0-1.2	0.6-7.1	Parent concrete exposure history Parent concrete quality	AMC Moisture condition	AMC can retain and release chlorides [56, 60]
Porosity (%)	1.1	23.3	AMC content AMC porosity/ITZ quality	Parent concrete grade Crushing method	Controls chloride ingress, freeze-thaw, and carbonation resistance [54, 58]
Crush Value (%)	4.04	15.2	Parent concrete grade AMC content	Crushing method	Weak mortar film reduces point-load resistance, mitigated by higher parent concrete grade [54]

[a] Factor hierarchy is based on cited literature; relative dominance may shift with RCA replacement level and mix design. AMC = adhered mortar content; NA = natural aggregate; ITZ = interfacial transition zone.

3.1 RCA Shape Properties

The shape of the RCA greatly depends on the crushing process to break the aggregates, similar to the NA. Common aggregate shapes include rounded, flaky, elongated, and angular [61]. The surface texture or morphology of the aggregates can be influenced significantly by the hardness, grain size, and pore characteristics of their parent materials. Smooth surfaces improve the workability of fresh concrete, whereas angular surfaces create a stronger bond between the mortar and aggregates, leading to higher strength. This is particularly important in applications where enhanced flexural strength or higher compressive strength is required. There are several test methods to determine the shape properties of aggregates, such as flakiness and elongation indices, angularity number of coarse aggregates, and index of aggregate particles' shape and texture [62].

Elongated and flaky aggregates require more water and sand in the mix to obtain suitable workability. They may also break during compaction. These adversely affect the strength of concrete. Thin and flat particles can reduce the strength of concrete when a load is applied to the flat side of the aggregate and are also prone to segregation and breakdown during compaction and mixing. The breaking of aggregates results in the creation of additional fine particles. Higher flakiness and elongation also reduce the workability and durability of concrete [63]. Elongated particles reduce the strength of concrete due to the reduction of bond strength between the aggregate and cement paste. In addition, higher cement content will be required to achieve a similar strength [64, 65].

3.2 Particle Density and Water Absorption

Particle density and water absorption are important properties for both natural and recycled aggregates in quality control. In general, the particle density of aggregates varies from 2000 to 2500 kg/m^3 depending on the composition of the crushed materials. The particle density also depends on aggregate size. Limbachiya [66] reported that RCA has 7-9% lower relative density compared to the natural aggregates in the saturated surface dry state. Sago-Crentsil et al. [67] reported a bulk density of 2394 kg/m^3 for RCA and 2890 kg/m^3 for natural aggregates. The decrease in density is due to the adhered mortar, which is lightweight compared to the natural aggregates.

Water absorption of RCA is generally higher compared to natural aggregates due to the higher porosity of the old mortar adhered to the recycled aggregates. Water absorption of natural aggregates ranges from 0.8 to 3.7%, whereas the corresponding absorption for recycled aggregates ranges from 3.7 to 8.7% (Table 1). Other studies showed a water absorption of 4.9-5.6 for RCA compared to 1.0-2.5% for natural aggregates [66, 67]. Li et al. [68] reported a decrease in the water absorption rate for RCA after carbonation. This was consistent with the results claimed by Li et al. [69].

3.3 Gradation/Particle Size Distribution

Gradation or size distribution of the aggregates is an important property that directly affects the fresh and hardened properties of the concrete, such as workability, porosity, permeability, strength, degree of compaction, and durability of the concrete. Similar to the virgin aggregate, RCA needs to be a continuous gradation to allow greater interaction between particles and provide greater compactness and improved mechanical properties. Gradation or size distribution of RCA is similar to natural aggregate and is based on general standards such as ASTM C33 [70] or EN 12620 [12]. Aggregate gradation or particle size distribution is also an important factor in selecting the pavement preservation method [71] or geotechnical projects [72].

3.4 LA Abrasion/Crushing

The Los Angeles (LA) abrasion test measures the pulverization that takes place for a given aggregate when subjected to impact, abrasion, and grinding. In general, a softer aggregate is expected to have a higher abrasion loss. A higher percentage loss indicates less resistance to abrasion while a load is applied. Virgin aggregates tend to have LA abrasion of about 10-20% mass loss; however, the corresponding values for RCAs are reported to be higher and between 20-45%. The higher value is due to the presence of cement paste which is more susceptible to abrasion than most aggregates [9, 54]. However, based on ASTM C131, aggregates for construction are required to have an abrasion loss of less than 50% for general construction and less than 40% for crushed stone for pavement. Despite the lower abrasion resistance for RCA, typically, their resistance is within the acceptance of the ASTM C131.

3.5 Adhered Mortar Content

Recycled concrete aggregate includes the coarse aggregate from the original concrete partially or fully surrounded by mortar from the crushed concrete, as shown in Figure 3. The amount of cement mortar attached is one of the significant factors affecting the material properties of RCA [52]. Adhered mortar content is affected by the number of crushing processes in the production plants. Increasing the number of crushing processes reduces the mortar content and improves the quality of aggregates [73]. Nevertheless, this also increases the production cost; therefore, a balance between the number of crushing stages and the quality of aggregate needs to be considered. There is concern that the original cement attached to the RCA may not have completely reacted with water during mixing. Crushing of concrete can expose unhydrated cement, which can react with water when RCA is used for new concrete, as suggested by Manzi et al. [74]. This may have positive and negative effects on new concrete. The cement can increase the strength of the new concrete by lowering the water-to-cement ratio. However, it can also increase the drying shrinkage, which may result in premature cracking in new concrete. Due to the importance of the adhered mortar content on the properties of the RCA, several test methods have been developed to quantify the adhered mortar content. These methods involve soaking aggregates in chemical solutions and/or subjecting aggregates to freeze-thaw cycling. These two methods remove the mortar content by chemical degradation and degradation due to mechanical stress allowing the quantity of adhered mortar to be measured. For example, ASTM C88-05 [75] uses sodium or magnesium sulfate solutions to remove mortar by chemical degradation. There are other methods, such as subjecting RCA to freeze-thaw cycling while soaked in sodium chloride in order to remove mortar through mechanical stress [76].

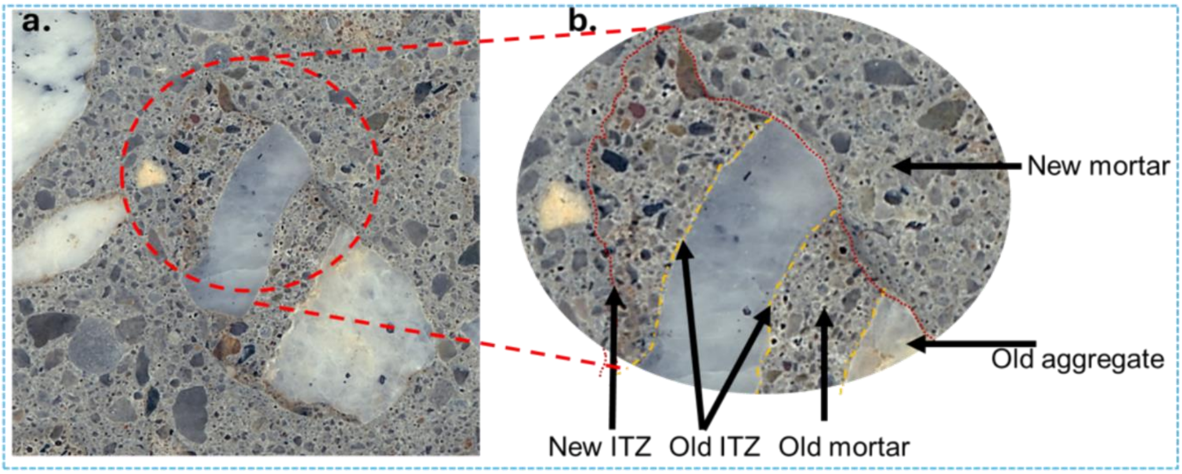

Figure 3 Typical image of concrete sample made with RCA, a. concrete surface with b. high magnification showing the border of new and old mortar and interfacial zone.

New concrete produced by RCA provides two interfacial transition zones (ITZ), one refers to the new ITZ between RCA and the new mortar matrix, and the other ITZ lies between the original aggregate in the RCA and old adhered mortar. Tam et al. [77] conducted microstructure studies of the RCA and provided SEM images highlighting these ITZs. The original cement content attached to NA in recycled aggregate is more porous than NA and therefore results in more water absorption. Etxeberria et al. [64] found that ITZ is the weakest region in concrete with RCA due to its higher porosity. However, Otsuki et al. [78] conducted Vickers micro hardness testing and concluded that the characteristic of the ITZ depends on the quality rather than the quantity of the adhered mortar.

It has been claimed that using a pozzolanic solution to treat RCA can enhance the strength of adhered mortar [15]. RCA immersed in a pozzolanic material, especially containing silica fume, can fill the pores and voids of adhered mortar [77].

3.6 Implication for Mix Design

The attachment of old mortar to the RCA results in a higher porosity compared to the natural aggregates. Higher porosity directly influences other mechanical properties such as water absorption, density, and strength properties of the concrete. Higher water absorption will affect the water volume available for the chemical reactions. Several authors [79, 80] suggested that in the case of RCA, an additional 10-15% water in the total mixing water may be required to improve workability. However, the addition of water consequently increases the w/c ratio and adversely affects the mechanical properties of concrete [81]. Some researchers [66, 82] proposed complementing the mixture with an equivalent volume of extra cement. Nevertheless, Laserna and Montero [83] showed that the strength of the recycled concrete is clearly influenced by the richness of the cement content.

There have been several investigations [84-88] to study the influence of pre-wetting recycled aggregates on the rheological behavior of concrete by varying the initial moisture of the RCA. Some researchers [84, 89] claimed that prewetting may introduce a potential solution to the high-water absorption of RCA. Malešev et al. [90] suggested increasing the water volume corresponding to 30 minutes of RCA water absorption in the middle of the mixing process. Rodrigues et al. [91] recommended washing the aggregate to remove the fine fraction adhered part of the soluble sulfate content to decrease the water absorption. Otsuki et al. [78] and Ryu [92] recommended using a double-step mixing method which they reported as adding water or aggregates in two stages to improve the interfacial transition zone surrounding RCA. Despite the fact that these methods may improve the strength of concrete, they introduce complexity to the mixing process and are difficult to implement in the current concrete manufacturing procedures.

In addition to these conventional approaches, recent studies have explored data-driven and machine learning (ML) methods to address the RCA variability and optimize mix design. These approaches aim to balance workability, mechanical performance, and durability by leveraging large data sets and predictive modeling techniques. For example, recent work on low-carbon recycled concrete has demonstrated the use of synthetic data augmentation techniques (e.g., CTGAN) combined with machine learning models to improve prediction accuracy under limited or heterogeneous datasets. These emerging methodologies provide a promising complement to traditional empirical and experimental approaches, particularly for the design of sustainable concrete systems where material variability remains a critical challenge [93].

4. Properties of Concrete Made with Recycled Concrete Aggregate

Aggregates make up about 60-75% of the concrete volume [15]. Complete or partially replacing virgin aggregates with recycled aggregates affects the properties of concrete, and there has been extensive research to investigate the fresh and hardened properties of RCA. It is generally accepted that concrete with RCA is expected to have higher porosity, higher shrinkage, and lower strength, and therefore, many countries avoid using RCA for concrete structural applications.

4.1 Fresh Properties

The constituent materials of recycled concrete aggregate have a large effect on the fresh properties of concrete, such as workability, air content, and density. Type of aggregate, aggregates maximum size, water absorption of aggregate, etc., have different effects on the fresh properties of concrete. The workability of fresh concrete refers to how easily it can be placed and finished without segregation and is affected by surface texture, aggregate size, and aggregate shape. In general, the use of RCA will require more water compared to mixes with natural aggregates to achieve desired workability [94, 95]. For example, Tabsh and Abdelfatah [96] concluded that concrete mixtures with recycled aggregates required an additional 10% water compared to the NA to provide similar workability. The moisture content of the RCA is another parameter that affects the workability of concrete mixtures with RCA. RCA has higher water absorption and, therefore, absorbs the water from the fresh mix, which in return, adversely affects the workability [64, 94, 97]. Poon et al. [98] observed bleeding of concrete for concrete mixes with surface-saturated dry RCA, and they concluded that the bleeding was responsible for the reduction of compressive strength compared to concrete with dry RCA or NA.

Shi et al. [15] discussed several pretreatment methods for RCA that include either removing or strengthening the adhered mortar from RCA. Typical methods to remove adhered mortar include mechanical grinding, heat grinding, and pre-soaking in acid. Other methods, such as polymer impregnation, pozzolanic slurry, immersion, accelerated carbonation curing, and bio-deposition methods, are claimed to strengthen the RCA [99]. Dimitrou et al. [10] reported that RCA with a rounder shape had higher workability than with more angular recycled aggregates. A similar conclusion is reported by Sagoe-Crentsil et al. [67].

Belangra et al. [100] concluded that the addition of admixtures at various percentages could increase the workability and hence decrease the w/c ratio in order to enhance the mechanical properties of concrete with RCA. The air content of fresh concrete containing RCA is more variable and often 0.6% higher compared to the fresh concrete with NA [101-103]. This is due to the air entrained and entrapped in the RCA.

4.2 Compressive Strength

Compressive strength, perhaps, is the most important property of the concrete with RCA and often is the primary factor in determining the classification of RCA. The compressive strength requirement of concrete is based on its application. For example, concrete with compressive strength less than 15 MPa is suitable to be used as concrete fill, 20 MPa for basement and foundation, 20-25 MPa for driveways, garages and industrial floor slabs, and higher than 70 MPa is for high-rise buildings [104].

The compressive strength of RAC depends on the water-to-cement ratio, the level of aggregate replacement, and the resistance of the aggregates to crushing [98, 105]. Based on available literature, the normalized compressive strength typically ranges from 0.70 to 1.00 for partial replacement and decreases to 0.40-0.90 for 100% RCA, depending on mix design and aggregate quality.

It is generally accepted that recycled concrete aggregates reduce the strength of concrete compared to comparable NA mixes. The reduction is higher when RCA replaces 100% of the NA. Henson and Narud [106] reported a decrease in compressive strength up to 30% when 100% NA was replaced with RCA. Similarly, other researchers [64, 107] observed a reduction in compressive strength between 12 to 25% with total replacement of RA. Nevertheless, there are cases where the reduction in compressive strength is more significant, reaching up to 60% [108] and even 76% [109] for 100% RCA. This reduction in strength could be partially attributed to the presence of adhered mortar, increased porosity, and weaker ITZ. However, there is no clear trend in the reduction of compressive strength and total replacement of RA. In some cases, comparable strength to NA is reported. Shayan and Xu [110] conducted a comprehensive study to investigate strength development and durability-related properties of RCA of 50 MPa strength-grade concrete. They used one commercially available source for RCA and investigated several different treatment methods, and also used silica fume in order to achieve similar mechanical and durability properties as concrete with natural aggregates. They concluded that RCA could be used to produce 50 MPa structural concrete with durability properties similar to concrete made with natural aggregates. In another investigation, Padmini et al. [111] crushed laboratory concrete with a compressive strength ranging from 31-58 MPa and used the resulting aggregate in new concrete. They concluded that the water absorption of recycled aggregates increases with an increase in the strength of the original concrete used to produce RCA. They also concluded that the strength of RCA increases with an increase in the maximum size of the aggregate. However, they reported that reducing the w/c ratio and increasing cement content is needed for RCA to achieve a similar compressive strength as NA. Similar conclusions were also claimed by Limbachiya et al. [112]. These findings highlight the critical role of mix design optimization and quality of sourced concrete in determining performance.

4.3 Flexural Strength

Flexural strength is another important property of concrete, particularly for pavement and slab applications. The properties of coarse aggregate have a greater influence on flexural strength than on compressive strength. Recent studies [113] have shown that aggregates with a rough surface and angular shapes provide a higher flexural strength compared to smooth and round shaped coarse aggregates due to the enhanced mechanical bond between the cementitious paste and the aggregate. The flexural strength of concrete is often estimated using empirical relationships with compressive strength. For concrete made with smooth and round shaped aggregates, the modulus of rupture (MOR) can be approximated as [114]:

$$MOR(MPa) = 0.7\sqrt{f'_c} \quad \left(MOR(psi) = 8\sqrt{f'_c}\right) \tag{2}$$

$$MOR(MPa) = 0.8\sqrt{f'_c} \quad \left(MOR(psi) = 10\sqrt{f'_c}\right) \tag{3}$$

For the case of concrete made with rough textured and angular shaped aggregate, Equation 2 will be changed to Equation 3.

The purpose of presenting Equations 2 and 3 is to provide a baseline predictive framework for estimating flexural strength based on compressive strength and aggregate characteristics. These relationships can also be used to evaluate the deviation of RCA behavior from conventional concrete.

Comparison with experimental results from the literature indicates that RCA generally follows a similar trend, although slight variations may occur due to weaker ITZ and higher porosity. Available studies suggest that normalized flexural strength typically ranges from 0.80 to 1.00, even at high RCA replacement levels, indicating that flexural strength is less sensitive to RCA incorporation than compressive strength. For example, Ravindrarajah and Tam [115] reported no significant difference in the flexural strength of conventional concrete and concrete made with RCA. Other researchers [90, 105] reported a reduction of up to 10% in split tensile strength for 100% RAC. The quality of the concrete used to produce RCA has a strong influence on flexural strength which relies on the bond strength of the mortar content of RCA [116].

4.4 Elastic Modulus

The elastic modulus of concrete is influenced by the cement paste, types of aggregate, the interfacial transition zone, and the strength of concrete [117]. In addition, similar to the other properties of concrete, elastic modulus also varies with the age of the concrete. In general, a lower elastic modulus for concrete with RCA is reported. Some researchers [118, 119] claimed that the effect on the elastic modulus is minimal with up to 30% replacement of NA with RCA. Other researchers reported a reduction of 20-40% when 100% RCA is used [120]. This reduction is related to the fact that the elastic modulus of concrete made with RCA is generally lower than for concrete made with natural aggregates because of the mortar on the aggregate surface.

4.5 Drying Shrinkage

Cementitious materials may exhibit significant drying shrinkage during their service life [121]. Shrinkage is related to volume change, and it can be a detrimental property of concrete, especially if the concrete is restrained. Shrinkage depends on the mix design parameters such as mix proportions, cement content, cement replacement materials, and admixtures used in the mix [121]. Shrinkage occurs in the form of plastic shrinkage at the early stages of curing, and then drying shrinkage occurs throughout the service life of concrete. The reduction is due to the loss of water in the form of vapor from concrete. In general, concrete with RCA shows higher shrinkage, which is attributed to water absorbed by the mortar content attached to RCA. Some studies [122, 123] suggested that long-term strain is higher for concrete with RCA compared to similar concrete with NA. They claimed that the higher strain is produced by shrinkage where concrete is not subjected to load, and shrinkage and creep for concrete subjected to load. There is some ongoing research in order to improve concrete with recycled aggregate using alkali-activated binder treatment to reduce shrinkage [124].

4.6 Freeze-Thaw

Freeze-thaw resistance is a measure of concrete’s ability to resist internal cracking due to forces inside the concrete generated during freeze-thaw cycles. ASTM C666 [125] is a common standard used to determine the freeze-thaw resistance of concrete. Concrete subjected to freeze-thaw cycles requires air entrainment based on the aggregate size and the degree of exposure. ACI 330R [114] categorizes concrete into three types based on exposure: mild, moderate, and severe. Mild exposure refers to climates where the concrete is not exposed to freezing or deicing salts. Severe exposure, on the other hand, refers to climates where concrete is expected to be exposed to deicing chemicals or continuous moisture before freezing. The ACI 330R [114] recommends air content percentages of 3.0, 4.5, and 6.5% for mild, moderate, and severe exposure, respectively, for concrete with a maximum aggregate size of 25 mm (1 in).

The freeze-thaw resistance of RCA is a major durability concern in cold regions due to its higher absorption, porosity, and adhered mortar. Further research is required to fully understand the freeze-thaw durability performance of RCA. Šeps et al. [126] reported a decrease in freeze-thaw resistance in concrete containing RCA. They suggested that RCA should only be used in concrete when it can be protected from freezing in moist conditions [126]. However, Huda and Alam [127] reported that the durability performance of RCA was satisfactory for concrete made with recycled coarse aggregates at a replacement rate of 50%.

Yamato et al. [128] also reported lower freeze-thaw resistance for concrete with RCA. However, they also suggested that this reduction in durability can be mitigated by partial use of recycled aggregate, reducing W/C, and increasing entraining air.

4.7 Alkali-Silica Reaction

Alkali-Silica Reaction (ASR) occurs due to the reaction of alkaline pore solution of hydrated cement paste and reactive silica phases within some aggregates [129]. The ASR mechanism results from several sequential reactions as described by Rajabpour et al. [130] as follows: dissolution of metastable silica, formation of nano-colloidal silica sol, gelation of the sol, and swelling of the gel. Brantley et al. [131] claimed that silica dissolution is often the slowest reaction among these reactions, and therefore, it controls the rate of ASR in concrete. It is very common to use high temperatures and higher alkalinity in order to speed up the ASR in concrete in lab settings. The extent of gel swelling relies on the availability of moisture and mass transport properties of concrete, with damage occurring at a limited rate in dry and dense concrete [132].

In order for an alkali-silica reaction to occur, several specific conditions must be met. These include the presence of reactive forms of silica in the aggregate, a high alkali (pH) pore solution, and sufficient surface area [133, 134]. If any of these conditions are absent, ASR will not take place. When the reaction occurs in the presence of water, it creates a gel, leading to expansion. This expansion induces internal stress, ultimately resulting in a reduction in the modulus of elasticity, flexural strength, and compressive strength.

There are a number of test methods for assessing the potential alkali reactivity of aggregates in mortar or concrete [135]. The accelerated mortar-bar test method (AMBT) as outlined in ASTM C1260 [136], and the concrete prism test (CPT) conducted at 38 ºC following ASTM C1293 [137], are the most common tests.

In general, the heterogeneity that may exist in the RCA with different origins add complexity to accurately assessing its potential for ASR [135]. One possibility is that the higher porosity of RCA due to the adhered mortar can accommodate some of the formed gel and can result in hiding or delaying the expansion. One can also use slag in mixes with RCA to help mitigate the potential for ASR [135].

4.8 Carbonation Resistance

The carbonation of concrete depends on factors such as the concentration of carbon dioxide that concrete structures are exposed to, pore distribution of the hardened concrete, moisture content, temperature, and the presence of the microcracks. In the case of concrete with normal aggregates, carbonation is widely studied. However, there is limited study for concrete with RCA. Resistance to carbonation for concrete with RCA has two main differences compared to concrete with natural aggregates [138]. First, RCA may have already carbonated before its use as concrete aggregate, subsequently leading to the local increase of the carbonation depth. Second, adhered mortar to the aggregate, which is porous, may carbonate considerably faster than the cement paste of the new concrete, which results in a local increase of the carbonation depth as well. On the other hand, Leemann [138] showed that new concrete made with RCA obtained from demolishing a strong concrete would result in a lower carbonation depth.

Ana et al. [139] determined the carbonation depth of concrete made with 25, 50, 75, and 100% RCA. Their results showed that the higher the replacement of RCA, the higher the carbonation depth will be. Similar results are also reported by Silva et al. [140], claiming that concrete with 100% RCA can exhibit carbonation depths up to almost 2.5 times greater than that of a corresponding concrete with NA. In another study, the carbonation depth was between 1.2 to 2 times higher for concrete with RCA than concrete with NA [141].

Nevertheless, some researchers reported similar or higher resistance to carbonation for concrete with RCA than NA [138]. For example, Limbachiya et al. [112] reported a decrease in carbonation depth with concrete made with 30% RCA compared to concrete with NA. The compressive strength of concrete made with RCA and NA was reported to be 39 MPa and 33 MPa, respectively. Similarly, Xiao et al. [142] reported a decrease in the carbonation depth of concrete with recycled aggregate concrete with the increase in the strength grades of the original concrete. Xiao et al. [142] suggested that the existence of higher mortar content in concrete with RCA (old mortar and new mortar) provides a larger quantity of materials available for carbonation, and therefore, the carbonation resistance will be improved. The use of superplasticizer is reported to lower the carbonation depth of the RA concrete than RA concrete without superplasticizer [143].

Some studies [144-146] show that carbonated RCA can increase the compressive strength of new concrete. For example, Lu et al. [144] showed that using carbonated RCA in new concrete can increase compressive strength compared to non-carbonated RCA aggregates. The authors reported the compressive strength of concrete with 100% non-carbonated RCA of 40 MPa. The corresponding compressive strength for concrete with 100% carbonated RCA was reported to be about 54 MPa. Lower water absorption and higher apparent density of carbonated RCA compared to non-carbonated RCA were responsible for improving the compressive strength.

4.9 Chloride Ion Penetration

Incorporating RCA increases the chloride penetration of new concrete [147]. Limbachiya et al. [112] reported a similar or moderate level of chloride concentration using RCA up to 30%. They claimed that concrete with higher than 30% RCA substantially increases the chloride concentration compared to concrete with NA. Higher compressive strength of concrete containing RCA tends to decrease the chloride concentration. In general, pore characteristics and strength of concrete are the major properties governing the resistance to chloride penetration. Therefore, lowering the w/c ratio of new concrete, reducing capillary pore volume, or refining the pore network significantly improves the resistance to chloride penetration of RCA concrete. Matias et al. [143] reported an improvement in chloride penetration resistance by using a high-performance superplasticizer. Using silica fume is also reported to decrease chloride ion penetration for concrete with RCA [112, 148]. Shicong and Poon [148] reported that the replacement of cement with 25% fly ash increases the resistance to chloride ion penetration of concrete with RCA.

4.10 Microstructure of RCA

X-ray diffraction (XRD) and Scanning Electron Microscopy (SEM) are analytical methods used to assess the mineralogical composition, microstructure, and surface properties of RCAs. XRD relies on the interaction between X-rays and crystalline materials. When X-rays interact with a crystalline object, they diffract at particular angles, resulting in a distinctive diffraction pattern. Analyzing this pattern allows for the identification of the crystalline phases of a material [149]. XRD helps the identification of the mineral composition of RCA and differentiates between crystalline phases, including quartz, calcite, and various silicate minerals [150]. This offers insights into the comprehensive mineralogical composition. XRD also reveals the amorphous content in RCA which helps understand the degree of hydration or amorphous phases present, influencing the overall performance of recycled aggregates.

SEM utilizes electron beams to scan the surface of a sample. The interaction of the electrons with the sample's atoms generates signals that can be used to create details of the surface morphology and composition at a micro to nanoscale [151]. It provides high-resolution images of the microstructure of RCAs, helping visualize surface roughness, porosity, and the distribution of distinct phases, thereby exposing the quality and characteristics of recycled aggregates. It also facilitates the measurement and characterization of particle size and morphology, which is critical for understanding the performance of RCA in concrete mixes. SEM is often used to reveal surface defects, cracks, and other features that may impact the overall durability of RCAs. In particular, SEM observations consistently show that RCA particles are surrounded by adhered old mortar, which introduces a more porous and heterogeneous ITZ compared to natural aggregates. This weak ITZ is characterized by loosely packed hydration products, higher microcrack density, and increased porosity, which directly influence the mechanical behavior of concrete.

The presence of adhered mortar leads to the formation of a multi-layer ITZ system, including the old ITZ from the original concrete, the new ITZ formed with fresh cement paste, and the interface between old and new mortar. This composite ITZ is generally weaker than that in conventional concrete and acts as a preferential zone for crack initiation and propagation. As a result, the reductions in compressive strength and elastic modulus discussed in Sections 4.2 and 4.4 can be directly attributed to the inferior quality of the ITZ. In addition, the higher water absorption of RCA may cause localized variations in the effective water-to-cement ratio near the aggregate surface, leading to non-uniform hydration and further weakening of the ITZ.

Yaowarat et al. [152] investigated the effect of polyvinyl alcohol to improve the compressive and flexural strength of concrete containing RCA. They used SEM and XRD in their investigation and found that polyvinyl alcohol forms a film around cement grains and prevents the water absorption for cement hydration process. This led to retard the hydration process and delay the initial and final setting times of polyvinyl alcohol cement. As a result, they reported a reduction in compressive strength, which can also be associated with changes in the microstructure and ITZ characteristics.

Jitsangiam et al. [153] used XRD and SEM to analyze high grade RCA and road base RCA. They observed a fabric hydration product (CSH), with a needle-like product (ettringite) on their surfaces and pores. They claimed that CSH and ettringite fill the pores and result in higher strength. Their result also showed that the introduction of nonactive materials such as bricks and tires reduces the amount of cohesive hydration products, weakens the microstructure, and consequently lowers the mechanical performance [153].

5. Recycled Concrete Aggregates Classification

The influence of RCA on the properties of the new concrete has led some countries, regions, or organizations in the world to have different methods of RCA classifications, and these methods often differ from each other. International Union of Laboratories and experts in construction materials, System and Structures (RILEM) [154] released a specification for RCA, categorizing the RCA into Class I, Class II, and Class III based on the saturated dry surface density and water absorption. Hong Kong [155] allowed 20 and 100% replacement for RCA by specifying limitations for properties such as the minimum dry particle density, max water absorption, maximum content of wood, metals, plastic, and clay lump, and sulfate contents. A maximum of 20% replacement of NA with RCA is allowed for structural concrete with maximum compressive strength of 35 MPa. 100% replacement with RCA is only allowed for less demanding concrete structures with maximum compressive strength of 20 MPa. This includes applications such as benches, flower beds, or cyclopean concrete.

On the other hand, in Japan, Industrial Standards (JIS) classified RA into 3 different categories such as Class H, Class M, and Class L, based on the maximum compressive strength values of concrete made from RCA. British Standard [156] divided RCA into three categories such as Class I, Class II, and Class III, based on sources of waste concrete.

The German standard “DIN 4226-100 Recycled Aggregates” [157] classified recycled aggregates into four types such as Type 1, Type 2, Type 3, and Type 4. This classification primarily depends on the composition of the original materials representing Type 1 as the best and Type 4 as the least quality. For example, Type 1 refers to recycled aggregates that contain more than 90% concrete and natural aggregates, less than 10% clinker and no porous bricks, or lime-sand bricks and less than 3% for other mineral components such as porous bricks, lightweight concrete, asphalt, glass, plastic, rubber or wood. The corresponding values for Type 4 recycled aggregates are at least 80% for concrete, natural aggregates, clinker and no porous bricks and lime-sand brick and up to 20% from mineral components such as porous bricks, lightweight aggregates, glass, ceramic, asphalt, etc. In addition, most of the classifications also indicate the percentage of concrete and other materials such as brick, masonry, ceramic, plastic, etc. This is due to the fact that these materials have a great influence on newly produced concrete. For example, several studies [158, 159] concluded that the addition of brick in RCA decreases the strength of new concrete.

Table 3 summarizes the classification of the recycled aggregates in several countries reported by Solyman [160]. It includes the application, allowable recycled materials, and the allowable concrete class. It can be seen that crushed concrete is allowed up to 100% for all these countries except Germany (Table 3). Germany only allows crushed concrete to be replaced by up 42%. The usage of recycled concrete is based on its concrete class which mainly refers to the strength ranging from 21 MPa (Denmark) up to 60 MPa (Europe). De Brito and Saikia [161] and Silva et al. [9] also reported that coarse aggregate can perform similarly to natural aggregates in a non-aggressive environment for concrete strength class C50/60. The Netherlands’ 20% structural limit aligns with conservative thresholds for chloride-exposed environments [162], while Japan’s restriction to subordinated applications reflects its tiered JIS classification system (JIS A 5021/5022/5023), as described by Koga et al. [163].

Table 3 Applications of RA in different countries [160].

Country	**Application**	**Allowable recycled materials (Volume%)**	**Allowable concrete class**	**Key literature support**
USA	Concrete, reinforcement, and pre-stressed concrete	0-100 only crushed concrete	All according to ACI 318-19	ACI 318-19 [164]
Europe	As in Eurocode 2 [165]	0-100 for particles >4 mm	According to aggregates up to strength C50/60	[9, 161]
Japan	subordinated applications	0-100 only crushed concrete	According to aggregates up to C30/37	[163]
Belgium	not in an aggressive environment	0-100	According to aggregates up to strength C30/37	[64]
Denmark	passive and moderator environment only	0-100	According to aggregate up to 21 MPa	[162]
Germany	Not for pre-stressed concrete or strong chemical attack	0-25	Up to B35	[166]
Netherlands	passive and moderator environment	20 only crushed concrete	Up to strength 40 MPa	[161, 162]

6. Structures with Recycled Concrete Aggregates

In general, applications of RCA can be divided into load and non-load bearing applications. The difference between them is the strength of the concrete. Here some of the applications that can be considered for construction using RAC are summarized. Their strength, service life expectation, frequency of their assessment, and repair operation are reviewed.

6.1 Airport Construction

Aggregates are a major part of all airport runway constructions, such as aggregate base, cement-treated base, asphalt, concrete, and fill materials. Standard specification for airport construction [167] describes the requirement for aggregates and other properties of concrete for airport construction. The weight loss of the fraction retained of the aggregate from the No.4 mesh sieve should not exceed 18% by weight when subjected to five cycles of sodium sulfate soundness according to ASTM C88 [75]. Gradation is another important criterion for this document. The crushed gravel and crushed stone should meet the requirements of one of the three gradations provided in the document to be accepted for concrete subbase course.

Compressive strength is another important property of concrete that needs to be specified for airport construction. Standard specification for airport construction [168] requires a compressive strength of 3.5 MPa (500 psi) at 7 days and 5.2 MPa (750 psi) at 28 days for a concrete subbase course. The document also requires air entrainment of between 6 to 10% according to ASTM C231 for gravel and stone aggregates and ASTM C173 for slag and other highly porous coarse aggregates. The slump of the mixture also needs to be 50 mm (2 in) according to ASTM C143 at the time of placing.

Airport pavement requires a minimum flexural strength of 4.1 MPa (600 psi) and compressive strength of 30 MPa (4400 psi) at 28 days. The w/c ratio, which influences these mechanical properties, is allowed up to a maximum of 0.50. In the case of severe freeze/thaw, deicer, or sulfate exposure, it may be necessary to use a w/c ratio lower than 0.50.

The Federal Aviation Administration (FAA) requires a service life of 20 years for airport pavement structures supporting aircraft traffic. However, it should be noted that due to the increase in passenger loads and also minimizing the downtime of airport pavement facilities, airline industries are undoubtedly under pressure to increase the service life.

6.2 Vehicle Parking Lots

Vehicle parking lots offer opportunities for utilizing sustainable materials, with concrete containing RCA being a common choice [169]. These parking lots typically have a service life of 30 years or more, after which the concrete can be recycled into aggregates and pavement subbase materials. Typical examples of concrete parking lots are public facilities, commercial developments, and business and multifunctional projects. They are found in various settings such as public facilities, commercial developments, and multifunctional projects, serving as car parking areas, access lanes, shopping center entrances, bus parking areas, and truck parking areas. While the primary function of these lots is vehicle parking, they often also serve as maneuvering areas and access points for delivery trucks. In terms of design and construction.

The main purpose of these is to park vehicles, but they may also provide maneuvering areas or access for delivery trucks. In general, there are many similarities between the design and construction of streets and highways with parking lots. In terms of design and construction, there are many similarities between parking lots and streets or highways.

ACI recommends workability with a slump of 38 mm (1½ in) or less for slip-form paving or 100 mm (4 in) when placed by hand or with vibrating [170]. In addition, the maximum aggregate size should be no greater than 1/3 the thickness of the slab. In the case of heavy traffic loads or when durability is critical, compressive strength of at least 28 MPa (4000 psi) is required for parking lots.

7. Challenges in Utilizing RCAs

The construction sector has been growing considerably in recent decades and this increased the global demand for concrete. As a result, global market for construction related aggregate reached about 48.3 billion tons in 2015 [171]. While the utilization of RCAs holds immense potential for sustainable construction projects, the multifaceted challenges associated with their implementation need to be addressed. Some of the challenges include quality standards and regulations (to ensure meeting specific criteria and wide acceptance), technological innovations (developing innovative processes to produce high-quality RCAs), life cycle assessment (understanding environmental impact of using RCA compared to NA), market acceptance and awareness (creating awareness and fostering market acceptance), economic viability (ensuring that production and use of recycled concrete aggregates remain economically viable), innovation in construction design (designing structures with RCAs in mind) and global collaboration (exchange of knowledge, practice and research finding).

8. Conclusions

The properties of recycled concrete aggregate and the properties of concrete incorporating recycled concrete aggregates were reviewed in this paper. The main difference between RCA and NA is the fact that RCA contains adhered old mortar, which affects the properties of new concrete. The adhered mortar increases the water absorption, increases LA abrasion loss, and reduces density of RCA. As a result, additional water, admixtures or mix design adjustments are often required to achieve the desired consistency. For mechanical and sustainability prospects, RCA concrete generally exhibits a reduction in compressive strength, elastic modulus, and, to a lesser extent, flexural strength, although these effects depend on replacement level, source quality, and mix design. With proper optimization, comparable performance can be achieved. The use of RCA also provides environmental benefits, including the reduction of construction waste and the conservation of natural resources, although these benefits depend on transportation and processing conditions. RCA represents a viable and sustainable alternative to natural aggregates, particularly when mechanical performance and environmental impacts are considered together, and future efforts should focus on improving material consistency and advancing optimized, data-driven mix design approaches.

Author Contributions

The authors confirm contribution to the paper as follows: study conception and design: S. Abubakri, data collection: S. Abubakri, G.R. Lomboy; analysis and interpretation of results: S. Abubakri, G.R. Lomboy, and D. Cleary; draft manuscript preparation: S. Abubakri. All authors have read and agreed to the published version of the manuscript.

Competing Interests

The authors declare no conflict of interest.

AI-Assisted Technologies Statement

Grammarly was used to check grammar and spelling during the preparation of this manuscript. All scientific content, data interpretation, and conclusions were developed independently by the author. The authors have thoroughly reviewed and edited the AI-assisted text to ensure its accuracy and accept full responsibility for the content of the manuscript.

References

1. Behera M, Bhattacharyya SK, Minocha AK, Deoliya R, Maiti S. Recycled aggregate from C&D waste & its use in concrete-A breakthrough towards sustainability in construction sector: A review. Constr Build Mater. 2014; 68: 501-516.
2. Sonawane TR, Pimplikar SS. Use of recycled aggregate concrete. Int J Eng Res Technol. 2013; 52. doi: 10.17577/IJERTV2IS1052.
3. Global Cement and Concrete Association. Cement and concrete around the world [Internet]. London, UK: Global Cement and Concrete Association; 2026. Available from: https://gccassociation.org/concretefuture/cement-concrete-around-the-world/.
4. Wang R, Yu N, Li Y. Methods for improving the microstructure of recycled concrete aggregate: A review. Constr Build Mater. 2020; 242: 118164.
5. Mansourkhaki A, Ameri M, Habibpour M, Daryaee D. The effect of polybutadiene rubber (PBR) on chemical and rheological properties of the binder including RAP. Constr Build Mater. 2020; 244: 118320.
6. Woodson RD. Causes of distress and deterioration of concrete. In: Concrete structures: Protection, repair and rehabilitation. Oxford, UK: Butterworth-Heinemann; 2009. pp. 19-29.
7. El-Reedy M. Steel-reinforced concrete structures: Assessment and repair of corrosion. Boca Raton, FL: CRC Press; 2007.
8. Newman J, Choo BS. Advanced concrete technology set. Amsterdam, Netherlands: Elsevier; 2003.
9. Silva RV, de Brito J, Dhir RK. Properties and composition of recycled aggregates from construction and demolition waste suitable for concrete production. Constr Build Mater. 2014; 65: 201-217.
10. Dimitriou G, Savva P, Petrou MF. Enhancing mechanical and durability properties of recycled aggregate concrete. Constr Build Mater. 2018; 158: 228-235.

11. Snyder MB, Cavalline TL, Fick G, Taylor P, Gross J. Recycling concrete pavement materials: A practitioner's reference guide [Internet]. Ames, IA: National Concrete Pavement Technology Center; 2018. Available from: https://trid.trb.org/View/1918795.
12. iTeh. EN 12620:2013: Aggregates for concrete [Internet]. Newark, DE: iTeh; 2013. Available from: https://standards.iteh.ai/catalog/standards/cen/aef412e6-36ce-49d3-afaa-5200d721ff84/en-12620-2013?srsltid=AfmBOooGxvyfADjxnG0kxeETrPwuRCyfeb7hApIFHpYn7PBnzN3VT_rR.
13. British Standards Institution. BS 8500-2:2015 Concrete - complementary British Standard to BS EN 206. Specification for constituent materials and concrete (+A1:2016) [Internet]. Enterprises; 2015. Available from: https://www.thenbs.com/PublicationIndex/Documents/Details?Pub=BSI&DocId=314335.
14. Butler LJ, West JS, Tighe SL. Towards the classification of recycled concrete aggregates: Influence of fundamental aggregate properties on recycled concrete performance. J Sustain Cem Based Mater. 2014; 3: 140-163.
15. Shi C, Li Y, Zhang J, Li W, Chong L, Xie Z. Performance enhancement of recycled concrete aggregate-A review. J Clean Prod. 2016; 112: 466-472.
16. Ouyang K, Liu J, Liu S, Song B, Guo H, Li G, et al. Influence of pre-treatment methods for recycled concrete aggregate on the performance of recycled concrete: A review. Resour Conserv Recycl. 2023; 188: 106717.
17. Gómez-Cano D, Arias-Jaramillo YP, Bernal-Correa R, Tobón JI. Effect of enhancement treatments applied to recycled concrete aggregates on concrete durability: A review. Mater Constr. 2023; 73: e308.
18. Fanijo EO, Kolawole JT, Babafemi AJ, Liu J. A comprehensive review on the use of recycled concrete aggregate for pavement construction: Properties, performance, and sustainability. Cleaner Mater. 2023; 9: 100199.
19. Pellegrino C, Faleschini F. Sustainability improvements in the concrete industry: Use of recycled materials for structural concrete production. London, UK: Springer; 2016.
20. Poon CS, Chan D. Effects of contaminants on the properties of concrete paving blocks prepared with recycled concrete aggregates. Constr Build Mater. 2007; 21: 164-175.
21. Garbarino E, Blengini GA. The economics of construction and demolition waste (C&DW) management facilities. In: Handbook of recycled concrete and demolition waste. Cambridge, UK: Woodhead Publishing; 2013. pp. 108-138.
22. Menon AH, Jayaraj GK. Comparative study of demolition methods. Int J Adv Sci Res Eng Trends. 2017; 2. Available from: https://www.ijasret.com/VolumeArticles/FullTextPDF/139_IJASRET_Comparative_Study_of_Demolition_Methods.pdf.
23. Mohammadi M, Mohammad SM, Roshanbin M, Lomboy GR, Abubakri S. Advances in concrete demolition technologies: A review of conventional and emerging methods for sustainable waste management. Eng. 2024; 5: 3174-3191.
24. Gambatese JA. Controlled concrete demolition using expansive cracking agents. J Constr Eng Manage. 2003; 129: 98-104.
25. Hinze J, Brown J. Properties of soundless chemical demolition agents. J Constr Eng Manage. 1994; 120: 816-827.

26. Rathi SO, Khandve PV. Demolition of buildings-An overview. Int J Adv Eng Res Dev. 2014; 1: 1-8.
27. Kasai Y. Demolition of concrete structures by heating. Concr Int. 1989; 11: 33-38.
28. Yuzbasi J. Fundamentals of controlled demolition in structures: Real-life applications, discrete element methods, monitoring, and artificial intelligence-based research directions. Buildings. 2025; 15: 3501.
29. Verian KP, Whiting NM, Olek J, Jain J, Snyder MB. Using recycled concrete as aggregate in concrete pavements to reduce materials cost. West Lafayette, Indiana: Joint Transportation Research Program, Indiana Department of Transportation and Purdue University; 2013; FHWA/IN/JTRP-2013/18. Available from: https://doi.org/10.5703/1288284315220.
30. Wilson J. Recycling of construction and demolition waste: The Dutch experience. Quarry Manage. 1996; 23: 12.
31. Ulsen C, Tseng E, Angulo SC, Landmann M, Contessotto R, Balbo JT, et al. Concrete aggregates properties crushed by jaw and impact secondary crushing. J Mater Res Technol. 2019; 8: 494-502.
32. Gress DL, Snyder MB, Sturtevant JR. Performance of rigid pavements containing recycled concrete aggregate. Transp Res Rec. 2009; 2113: 99-107.
33. Cleary DB. Recycled concrete aggregate in Portland cement concrete [Internet]. Trenton, NJ: New Jersey Department of Transportation; 2013. Available from: https://rosap.ntl.bts.gov/view/dot/25558.
34. Kosmatka SH, Kerkhoff B, Panarese WC. Design and control of concrete mixtures. Washington, D.C.: Portland Cement Association; 2002.
35. Mulheron M, O’Mahony MM. Properties and performance of recycled aggregates. Highw Transp. 1990; 37: 35-37.
36. Hosseini SA, Asghari V, Liu X, Hsu SC, Poon CS. Cross-country life cycle assessment of construction and demolition waste recycling with evaluation of energy use, carbon emissions, and regional trade-offs. Sci Rep. 2025; 15: 41377.
37. Dacić A, Mester-Szabo E, Fenyvesi O, Szalay Z. Life cycle assessment of concrete incorporating all concrete recycling products. Case Stud Constr Mater. 2024; 21: e03910.
38. Gangolells M, Casals M, Forcada N, Macarulla M. Analysis of the implementation of effective waste management practices in construction projects and sites. Resour Conserv Recycl. 2014; 93: 99-111.
39. Duran X, Lenihan H, O’regan B. A model for assessing the economic viability of construction and demolition waste recycling-the case of Ireland. Resour Conserv Recycl. 2006; 46: 302-320.
40. Martínez-Lage I, Vázquez-Burgo P, Velay-Lizancos M. Sustainability evaluation of concretes with mixed recycled aggregate based on holistic approach: Technical, economic and environmental analysis. Waste Manage. 2020; 104: 9-19.
41. Zhang C, Hu M, Di Maio F, Sprecher B, Yang X, Tukker A. An overview of the waste hierarchy framework for analyzing the circularity in construction and demolition waste management in Europe. Sci Total Environ. 2022; 803: 149892.
42. Tam VW. Comparing the implementation of concrete recycling in the Australian and Japanese construction industries. J Clean Prod. 2009; 17: 688-702.
43. Scharff H. Landfill reduction experience in the Netherlands. Waste Manage. 2014; 34: 2218-2224.

44. Obla K, Kim H, Lobo CL. Crushed returned concrete as aggregates for new concrete [Internet]. Silver Spring, MD: National Ready Mixed Concrete Association; 2007. Available from: https://www.naylornetwork.com/nrc-nwl/pdf/CCA_Study_Final_Report9-07.pdf.
45. Blengini GA, Garbarino E. Resources and waste management in Turin (Italy): The role of recycled aggregates in the sustainable supply mix. J Clean Prod. 2010; 18: 1021-1030.
46. Golafshani EM, Kim T, Behnood A, Ngo T, Kashani A. Sustainable mix design of recycled aggregate concrete using artificial intelligence. J Clean Prod. 2024; 442: 140994.
47. Fan M, Li Y, Shen J, Jin K, Shi J. Multi-objective optimization design of recycled aggregate concrete mixture proportions based on machine learning and NSGA-II algorithm. Adv Eng Software. 2024; 192: 103631.
48. Zhang Y, Peng J, Wang Z, Xi M, Liu J, Xu L. Machine learning-assisted sustainable mix design of waste glass powder concrete with strength-cost-CO_2 emissions trade-offs. Buildings. 2025; 15: 2640.
49. Wang S, Xia P, Gong F, Zeng Q, Chen K, Zhao Y. Multi objective optimization of recycled aggregate concrete based on explainable machine learning. J Clean Prod. 2024; 445: 141045.
50. Makul N, Fediuk R, Amran M, Zeyad AM, de Azevedo AR, Klyuev S, et al. Capacity to develop recycled aggregate concrete in South East Asia. Buildings. 2021; 11: 234.
51. Marvila M, de Matos P, Rodríguez E, Monteiro SN, de Azevedo AR. Recycled aggregate: A viable solution for sustainable concrete production. Materials. 2022; 15: 5276.
52. Abbas A, Fathifazl G, Fournier B, Isgor OB, Zavadil R, Razaqpur AG, et al. Quantification of the residual mortar content in recycled concrete aggregates by image analysis. Mater Charact. 2009; 60: 716-728.
53. Reza F, Wilde WJ. Evaluation of recycled aggregates test section performance [Internet]. St. Paul, MN: MnDOT Research Services & Library; 2017. Available from: https://kutcresources.ku.edu/storage/1621441388_201706.pdf.
54. Xiao JZ. Recycled aggregate concrete. Berlin, Heidelberg: Springer; 2018.
55. Hubert J, Zhao Z, Michel F, Courard L. Effect of crushing method on the properties of produced recycled concrete aggregates. Buildings. 2023; 13: 2217.
56. Verian KP, Ashraf W, Cao Y. Properties of recycled concrete aggregate and their influence in new concrete production. Resour Conserv Recycl. 2018; 133: 30-49.
57. Meng S, Shi Z, Ouyang X. Comparison of the effects of carbon-based and inorganic nanomaterials on early cement hydration. Constr Build Mater. 2024; 421: 135705.
58. Muhammad F, Harun M, Ahmed A, Kabir N, Khalid HR, Hanif A. Influence of bonded mortar on recycled aggregate concrete properties: A review. Constr Build Mater. 2024; 432: 136564.
59. Gebremariam HG, Taye S, Tarekegn AG. Disparity in research findings on parent concrete strength effects on recycled aggregate quality as a challenge in aggregate recycling. Case Stud Constr Mater. 2023; 19: e02342.
60. Gebremariam HG, Taye S, Tarekegn AG. Parent concrete strength effects on the quality of recycled aggregate concrete: A review. Heliyon. 2024; 10: e26212.
61. Marie I, Mujalli R. Effect of design properties of parent concrete on the morphological properties of recycled concrete aggregates. Eng Sci Technol Int J. 2019; 22: 334-345.
62. ASTM. ASTM D4791: Standard test method for flat particles, elongated particles, or flat and elongated particles in Coarse Aggregate [Internet]. West Conshohocken, PA: ASTM; 2019.

Available from: https://www.scribd.com/document/916750204/ASTM-D4791-19-Flaky-Elongeted-Partical-of-Coarse-Aggregate.

63. Nayak NV, Jain AK. Handbook on Advanced Concrete Technology. Oxford, UK: Alpha Science International; 2012.
64. Etxeberria M, Vázquez E, Marí A, Barra M. Influence of amount of recycled coarse aggregates and production process on properties of recycled aggregate concrete. Cem Concr Res. 2007; 37: 735-742.
65. Pitso RI, Mostafa MM, Elsaigh WA. Incorporation of recycled concrete aggregates as road pavement material in South Africa. Int J Pavement Res Technol. 2026; 19: 199-207.
66. Limbachiya MC, Leelawat T, Dhir RK. Use of recycled concrete aggregate in high-strength concrete. Mater Struct. 2000; 33: 574-580.
67. Sagoe-Crentsil KK, Brown T, Taylor AH. Performance of concrete made with commercially produced coarse recycled concrete aggregate. Cem Concr Res. 2001; 31: 707-712.
68. Li Y, Zhang S, Wang R, Zhao Y, Men C. Effects of carbonation treatment on the crushing characteristics of recycled coarse aggregates. Constr Build Mater. 2019; 201: 408-420.
69. Li L, Poon CS, Xiao J, Xuan D. Effect of carbonated recycled coarse aggregate on the dynamic compressive behavior of recycled aggregate concrete. Constr Build Mater. 2017; 151: 52-62.
70. ASTM. ASTM C33/C33M-18: Standard Specification for Concrete Aggregates [Internet]. West Conshohocken, PA: ASTM International; 2018. Available from: https://store.astm.org/c0033_c0033m-18.html.
71. Pourhassan A, Gheni A, ElGawady M. Effect of aggregate size on the retention of conventional and rubberized chip seal. Proceedings of the 20th IABSE Congress, New York City 2019: The Evolving Metropolis; 2019 September 04-06; New York, NY. Zurich, Switzerland: IABSE.
72. MotahariTabari S, Shooshpasha I. Evaluation of coarse-grained mechanical properties using small direct shear test. Int J Geotech Eng. 2021; 15: 667-679.
73. De Juan MS, Gutiérrez PA. Study on the influence of attached mortar content on the properties of recycled concrete aggregate. Constr Build Mater. 2009; 23: 872-877.
74. Manzi S, Mazzotti C, Bignozzi MC. Short and long-term behavior of structural concrete with recycled concrete aggregate. Cem Concr Compos. 2013; 37: 312-318.
75. ASTM. Standard C 88-05: Standard Test Method for Soundness of Aggregates by Use of Sodium Sulphate or Magnesium Sulphate [Internet]. West Conshohocken, PA: ASTM International; 2009. Available from: https://www.scribd.com/document/734973535/ASTM-C88-Soundness-of-Aggregates#google_vignette.
76. Akbarnezhad A, Ong KC, Zhang MH, Tam CT. Acid treatment technique for determining the mortar content of recycled concrete aggregates. J Test Eval. 2013; 41: 441-450.
77. Tam VW, Gao XF, Tam CM. Microstructural analysis of recycled aggregate concrete produced from two-stage mixing approach. Cem Concr Res. 2005; 35: 1195-1203.
78. Otsuki N, Miyazato SI, Yodsudjai W. Influence of recycled aggregate on interfacial transition zone, strength, chloride penetration and carbonation of concrete. J Mater Civ Eng. 2003; 15: 443-451.
79. Hansen TC. Recycling of demolished concrete and masonry. Boca Raton, FL: CRC Press; 1992.
80. Sri Ravindrarajah R, Loo YH, Tam CT. Recycled concrete as fine and coarse aggregates in concrete. Mag Concr Res. 1987; 39: 214-220.

81. Lima C, Caggiano A, Faella C, Martinelli E, Pepe M, Realfonzo R. Physical properties and mechanical behaviour of concrete made with recycled aggregates and fly ash. Constr Build Mater. 2013; 47: 547-559.
82. Wattanasiriwech D, Saiton A, Wattanasiriwech S. Paving blocks from ceramic tile production waste. J Clean Prod. 2009; 17: 1663-1668.
83. Laserna S, Montero J. Influence of natural aggregates typology on recycled concrete strength properties. Constr Build Mater. 2016; 115: 78-86.
84. Le T, Rémond S, Le Saout G, Garcia-Diaz E. Fresh behavior of mortar based on recycled sand-influence of moisture condition. Constr Build Mater. 2016; 106: 35-42.
85. Montero J, Laserna S. Influence of effective mixing water in recycled concrete. Constr Build Mater. 2017; 132: 343-352.
86. García-González J, Rodríguez-Robles D, Juan-Valdés A, Morán-del Pozo JM, Guerra-Romero MI. Pre-saturation technique of the recycled aggregates: Solution to the water absorption drawback in the recycled concrete manufacture. Materials. 2014; 7: 6224-6236.
87. Brand AS, Roesler JR, Salas A. Initial moisture and mixing effects on higher quality recycled coarse aggregate concrete. Constr Build Mater. 2015; 79: 83-89.
88. Khoury E, Cazacliu B, Remond S. Impact of the initial moisture level and pre-wetting history of recycled concrete aggregates on their water absorption. Mater Struct. 2017; 50: 229.
89. Belin P, Habert G, Thiery M, Roussel N. Cement paste content and water absorption of recycled concrete coarse aggregates. Mater Struct. 2014; 47: 1451-1465.
90. Malešev M, Radonjanin V, Marinković S. Recycled concrete as aggregate for structural concrete production. Sustainability. 2010; 2: 1204-1225.
91. Rodrigues F, Carvalho MT, Evangelista L, De Brito J. Physical-chemical and mineralogical characterization of fine aggregates from construction and demolition waste recycling plants. J Clean Prod. 2013; 52: 438-445.
92. Ryu JS. Improvement on strength and impermeability of recycled concrete made from crushed concrete coarse aggregate. J Mater Sci Lett. 2002; 21: 1565-1567.
93. Liu J, Wang S, Chen K, Wang K, Fan Y, Wang Q. Synthetic data augmentation and integrated prediction framework for low-carbon recycled concrete: Leveraging CTGAN and multiple ML models stacking. J Clean Prod. 2026; 543: 147599.
94. Topcu IB, Şengel S. Properties of concretes produced with waste concrete aggregate. Cem Concr Res. 2004; 34: 1307-1312.
95. Pedro D, De Brito J, Evangelista L. Influence of the use of recycled concrete aggregates from different sources on structural concrete. Constr Build Mater. 2014; 71: 141-151.
96. Tabsh SW, Abdelfatah AS. Influence of recycled concrete aggregates on strength properties of concrete. Constr Build Mater. 2009; 23: 1163-1167.
97. Ngwenya LM, Franklin SO. Influence of recycled coarse aggregate on some properties of fresh and hardened concrete. Int J Innov Sci Eng Technol. 2015; 2: 257-264.
98. Poon CS, Shui ZH, Lam L, Fok H, Kou SC. Influence of moisture states of natural and recycled aggregates on the slump and compressive strength of concrete. Cem Concr Res. 2004; 34: 31-36.
99. Ouyang K, Shi C, Chu H, Guo H, Song B, Ding Y, et al. An overview on the efficiency of different pretreatment techniques for recycled concrete aggregate. J Clean Prod. 2020; 263: 121264.

100. Belagraa L, Abdelaziz M, Miloud B. Study of the physico-mechanical properties of a recycled concrete incorporating admixtures by the means of NDT methods. Procedia Eng. 2015; 108: 80-92.
101. Ben Nakhi A, Alhumoud JM. Effects of recycled aggregate on concrete mix and exposure to chloride. Adv Mater Sci Eng. 2019; 2019: 7605098.
102. Ojha PN, Arora VV, Trivedi A, Singh A, Singh B, Kaushik N. Experimental investigations on use of C&D waste as an alternative to natural aggregates in concrete. Sustain Struct Mater. 2021; 4: 58-70.
103. Safiuddin M, Alengaram UJ, Rahman MM, Salam MA, Jumaat MZ. Use of recycled concrete aggregate in concrete: A review. J Civ Eng Manage. 2013; 19: 796-810.
104. Neville GB. The strength of concrete. In: Concrete manual: 2012 IBC and ACI 318-11 concrete quality and field practices. Washington, D.C.: International Code Council; 2012. pp. 23-42.
105. Ajdukiewicz A, Kliszczewicz A. Influence of recycled aggregates on mechanical properties of HS/HPC. Cem Concr Compos. 2002; 24: 269-279.
106. Hansen TC, Narud H. Strength of recycled concrete made from crushed concrete coarse aggregate. Concr Int. 1983; 5: 79-83.
107. Yang KH, Chung HS, Ashour A. Influence of type and replacement level of recycled aggregates on concrete properties. ACI Mater J. 2008; 105: 289-296.
108. Bairagi NK, Ravande K, Pareek VK. Behaviour of concrete with different proportions of natural and recycled aggregates. Resour Conserv Recycl. 1993; 9: 109-126.
109. Katz A. Properties of concrete made with recycled aggregate from partially hydrated old concrete. Cem Concr Res. 2003; 33: 703-711.
110. Shayan A, Xu A. Performance and properties of structural concrete made with recycled concrete aggregate. Mater J. 2003; 100: 371-380.
111. Padmini AK, Ramamurthy K, Mathews MS. Influence of parent concrete on the properties of recycled aggregate concrete. Constr Build Mater. 2009; 23: 829-836.
112. Limbachiya M, Meddah MS, Ouchagour Y. Performance of Portland/silica fume cement concrete produced with recycled concrete aggregate. ACI Mater J. 2012; 109: 91-100.
113. Ichino H, Kuwahara N, Beppu M, Williamson EB, Himi A. Effects of the shape, size, and surface roughness of glass coarse aggregate on the mechanical properties of two-stage concrete. Constr Build Mater. 2024; 411: 134296.
114. American Concrete Institute. ACI PRC-330-08 Guide for the Design and Construction of Concrete Parking Lots [Internet]. Farmington Hills, MI: American Concrete Institute; 2008. Available from: https://www.concrete.org/store/productdetail.aspx?ItemID=33008&Format=PROTECTED_PDF&Language=English&Units=US_AND_METRIC.
115. Sri Ravindrarajah R, Tam CT. Properties of concrete made with crushed concrete as coarse aggregate. Mag Concr Res. 1985; 37: 29-38.
116. Anderson KW, Uhlmeyer JS, Russell MA. Use of recycled concrete aggregate in PCCP: Literature search [Internet]. Olympia, WA: Washington State Department of Transportation; 2009. Available from: http://www.wsdot.wa.gov/research/reports/fullreports/726.1.pdf.
117. Neville AM. Properties of concrete. London, UK: Pearson Education; 2011.
118. Limbachiya MC, Leelawat T, Dhir RK. RCA concrete: A study of properties in the fresh state, strength development and durability. In: Sustainable construction: Use of recycled concrete aggregate - Proceedings of the International Symposium organised by the Concrete Technology

Unit, University of Dundee and held at the Department of Trade and Industry Conference Centre; 1998 November 11-12; London, UK. London, UK: Thomas Telford. pp. 227-237.

119. Dhir RK, Paine KA. Suitability and practicality of using coarse RCA in normal and high-strength concrete. Proceedings of the 1st International Conference on Sustainable Construction: Waste Management; 2004 June 10-12; Singapore.
120. Silva RV, de Brito J, Dhir RK. Establishing a relationship between modulus of elasticity and compressive strength of recycled aggregate concrete. J Clean Prod. 2016; 112: 2171-2186.
121. Mangat PS, Abubakri S, Grigoriadis K. Bond of steel reinforcement with microwave cured concrete repair mortars. Mater Struct. 2017; 50: 249.
122. Domingo A, Lázaro C, Gayarre FL, Serrano MA, López-Colina C. Long term deformations by creep and shrinkage in recycled aggregate concrete. Mater Struct. 2010; 43: 1147-1160.
123. Seara-Paz S, González-Fonteboa B, Martínez-Abella F, González-Taboada I. Time-dependent behaviour of structural concrete made with recycled coarse aggregates. Creep and shrinkage. Constr Build Mater. 2016; 122: 95-109.
124. Damrongwiriyanupap N, Wachum A, Khansamrit K, Detphan S, Hanjitsuwan S, Phoo-ngernkham T, et al. Improvement of recycled concrete aggregate using alkali-activated binder treatment. Mater Struct. 2022; 55: 11.
125. ASTM. ASTM C666-97: Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing [Internet]. West Conshohocken, PA: ASTM; 2017. Available from: https://store.astm.org/standards/c666.
126. Šeps K, Fládr J, Broukalová I. Resistance of recycled aggregate concrete to freeze-thaw and deicing salts. Procedia Eng. 2016; 151: 329-336.
127. Huda SB, Shahria Alam M. Mechanical and freeze-thaw durability properties of recycled aggregate concrete made with recycled coarse aggregate. J Mater Civ Eng. 2015; 27. doi: 10.1061/(ASCE)MT.1943-5533.0001237.
128. Yamato T, Emoto Y, Soeda M. Mechanical properties, drying shrinkage and resistance to freezing and thawing of concrete using recycled aggregate. Spec Publ. 1998; 179: 105-122.
129. Cai Y, Xuan D, Poon CS. Effects of nano-SiO_2 and glass powder on mitigating alkali-silica reaction of cement glass mortars. Constr Build Mater. 2019; 201: 295-302.
130. Rajabipour F, Giannini E, Dunant C, Ideker JH, Thomas MD. Alkali-silica reaction: Current understanding of the reaction mechanisms and the knowledge gaps. Cem Concr Res. 2015; 76: 130-146.
131. Brantley SL, Kubicki JD, White AF. Kinetics of water-rock interaction. New York, NY: Springer; 2008.
132. Rutkauskas A, Nagrockienė D, Skripkiūnas G. Cement type influence on alkali-silica reaction in concrete with crushed gravel aggregate. IOP Conf Ser Mater Sci Eng. 2017; 251: 012032.
133. Bangert F, Kuhl D, Meschke G. Chemo-hygro-mechanical modelling and numerical simulation of concrete deterioration caused by alkali-silica reaction. Int J Numer Anal Methods Geomech. 2004; 28: 689-714.
134. Pacheco-Torgal F, Ding Y. Handbook of recycled concrete and demolition waste. Amsterdam, Netherlands: Elsevier; 2013.
135. Barreto Santos M, De Brito J, Santos Silva A. A review on alkali-silica reaction evolution in recycled aggregate concrete. Materials. 2020; 13: 2625.

136. ASTM. ASTM C1260-21: Standard Test Method for Potential Alkali Reactivity of Aggregates (Mortar-Bar Method) [Internet]. West Conshohocken, PA: ASTM; 2021. Available from: https://store.astm.org/c1260-21.html.
137. ASTM. ASTM C1293-20a: Standard Test Method for Determination of Length Change of Concrete Due to Alkali-Silica Reaction [Internet]. West Conshohocken, PA: ASTM; 2020. Available from: https://store.astm.org/c1293-20a.html.
138. Leemann A, Loser R. Carbonation resistance of recycled aggregate concrete. Constr Build Mater. 2019; 204: 335-341.
139. Werle AP, Kulakowski MP, de Souza Kazmierczak C, Sentena JA. Carbonation in concrete with recycled concrete aggregates. Proceedings of the XII International Conference on Durability of Building Materials and Components; 2011 April 12-15; Porto, Portugal.
140. Silva RV, Neves R, De Brito J, Dhir RK. Carbonation behaviour of recycled aggregate concrete. Cem Conc Compos. 2015; 62: 22-32.
141. Bravo M, De Brito J, Pontes J, Evangelista L. Durability performance of concrete with recycled aggregates from construction and demolition waste plants. Constr Build Mater. 2015; 77: 357-369.
142. Xiao J, Lei B, Zhang C. On carbonation behavior of recycled aggregate concrete. Sci China Technol Sci. 2012; 55: 2609-2616.
143. Matias D, de Brito J, Rosa A, Pedro D. Durability of concrete with recycled coarse aggregates: Influence of superplasticizers. J Mater Civ Eng. 2014; 26. doi: 10.1061/(ASCE)MT.1943-5533.000096.
144. Lu B, Shi C, Cao Z, Guo M, Zheng J. Effect of carbonated coarse recycled concrete aggregate on the properties and microstructure of recycled concrete. J Clean Prod. 2019; 233: 421-428.
145. Tam VW, Butera A, Le KN. Carbon-conditioned recycled aggregate in concrete production. J Clean Prod. 2016; 133: 672-680.
146. Zhang J, Shi C, Li Y, Pan X, Poon CS, Xie Z. Influence of carbonated recycled concrete aggregate on properties of cement mortar. Constr Build Mater. 2015; 98: 1-7.
147. Dosho Y. Effect of mineral admixtures on the performance of low-quality recycled aggregate concrete. Crystals. 2021; 11: 596.
148. Shicong K, Poon CS. Compressive strength, pore size distribution and chloride-ion penetration of recycled aggregate concrete incorporating class-F fly ash. J Wuhan Univ Technol Mat Sci Ed. 2006; 21: 130-136.
149. Das S, Biswas J, Siddique MI. Mechanical characterization of materials using advanced microscopy techniques. World J Adv Res Rev. 2024; 21: 274-283.
150. Bilir T, Aygörmez Y, Bastan Z, Uysal M, Aygun BF. Unraveling the characteristics of geopolymer mortars: A deep dive into the impact of marble powder as fine aggregate and varied activators. Constr Build Mater. 2024; 422: 135767.
151. Agrawal M, Prasad VV, Nijhawan G, Jalal SS, Rajalakshmi B, Dwivedi SP. Retracted: A comprehensive review of electron microscopy in materials science: Technological advances and applications. E3S Web Conf. 2024; 505: 01029.
152. Yaowarat T, Horpibulsuk S, Arulrajah A, Mirzababaei M, Rashid ASA. Compressive and flexural strength of polyvinyl alcohol-modified pavement concrete using recycled concrete aggregates. J Mater Civ Eng. 2018; 30. doi: 10.1061/(ASCE)MT.1943-5533.000223.

153. Jitsangiam P, Boonserm K, Phenrat T, Chummuneerat S, Chindaprasirt P, Nikraz H. Recycled concrete aggregates in roadways: Laboratory examination of self-cementing characteristics. J Mater Civ Eng. 2015; 27. doi: 10.1061/(ASCE)MT.1943-5533.00012.
154. Hendriks CF, Pietersen HS. Report 22: Sustainable Raw Materials: Construction and Demolition Waste – State-of-the-Art Report of RILEM Technical Committee 165-SRM. RILEM Publications; 2000.
155. Development Bureau. WBTC No.12/2002: Specifications Facilitating the Use of Recycled Aggregates [Internet]. Hong Kong, China: Development Bureau; 2002. Available from: https://www.devb.gov.hk/filemanager/technicalcirculars/en/upload/138/1/wb1202.pdf.
156. British Standards Institution. BS 6543:1985 Guide to use of industrial by-products and waste materials in building and civil engineering [Internet]. London, UK: British Standards Institution; 1985. Available from: https://codehub.building.govt.nz/resources/bs-65431985#!#resource-detail.
157. DIN Media. DIN 4226-100:2002-02: Aggregates for concrete and mortar - Part 100: Recycled aggregates [Internet]. Berlin, Germany: DIN Media; 2002. Available from: https://www.dinmedia.de/en/standard/din-4226-100/44711226.
158. Poon CS, Chan D. Feasible use of recycled concrete aggregates and crushed clay brick as unbound road sub-base. Constr Build Mater. 2006; 20: 578-585.
159. Peng HS, Chen HJ, Yen T. Strength and workability of recycled aggregate concrete. Proceedings of the International Conference Composites in Constructions - CCC2003; 2003 September 16-19; Cosenza, Italy.
160. Solyman M. Classification of recycled sands and their applications as fine aggregates for concrete and bituminous mixtures [Internet]. Kassel, Germany: University of Kassel; 2005. Available from: https://urn.fi/urn:nbn:de:hebis:34-2818.
161. De Brito J, Saikia N. Recycled aggregate in concrete: Use of industrial, construction and demolition waste. London, UK: Springer Science & Business Media; 2013.
162. McNeil K, Kang TH. Recycled concrete aggregates: A review. Int J Concr Struct Mater. 2013; 7: 61-69.
163. Koga H, Katahira H, Shimata A. The introduction of recycled-aggregate concrete specifications in Japan and the research into the freezing-thawing resistance of recycled-aggregate concrete. J Mater Cycles Waste Manage. 2022; 24: 1207-1215.
164. Ossa A, García JL, Botero E. Use of recycled construction and demolition waste (CDW) aggregates: A sustainable alternative for the pavement construction industry. J Clean Prod. 2016; 135: 379-386.
165. European Committee for Standardization. EN 1992-1-1: Eurocode 2: Design of concrete structures- Part. 1-1: General rules and rules for buildings. Cairo, Egypt: CEN; 2004.
166. Breit W, Burgmann S. Concrete with recycled aggregates-update of the application rules in germany and outlook. ce/pap. 2023; 6: 956-963.
167. Wisconsin Bureau of Aeronautics. State of Wisconsin, Bureau of Aeronautics: Standard Specifications for Airport Construction [Internet]. Madison, WI: Wisconsin Bureau of Aeronautics; 1998. Available from: https://wisconsindot.gov/Documents/doing-bus/aeronautics/airports/mstrspecbook.pdf.
168. U.S. Department of Transportation Federal Aviation Administration. Standard Specifications for Construction of Airports: AC 150/5370-10H [Internet]. Washington, D.C.: Federal Aviation

Administration; 2018. Available from: https://www.faa.gov/documentLibrary/media/Advisory_Circular/150-5370-10H.pdf.

169. Merten FR, Dutra VF, Strieder HL, Graeff ÂG. Clogging and maintenance evaluation of pervious concrete pavements with recycled concrete aggregate. Constr Build Mater. 2022; 342: 127939.

170. American Concrete Institute. ACI PRC-330.2-17: Guide for the Design and Construction of Concrete Site Paving for Industrial and Trucking Facilities (Reapproved 2020) [Internet]. Farmington Hills, MI: American Concrete Institute; 2020. Available from: https://www.concrete.org/store/productdetail.aspx?ItemID=330217&Format=PROTECTED_PDF&Language=English&Units=US_AND_METRIC.

171. Zhang Y, Luo W, Wang J, Wang Y, Xu Y, Xiao J. A review of life cycle assessment of recycled aggregate concrete. Constr Build Mater. 2019; 209: 115-125.