recycling

Review

Recycled Concrete Aggregate in Asphalt Mixtures: A Review

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Abstract

Effective management and handling of construction and demolition waste (CDW) can yield significant technical and environmental benefits for road pavement construction. This article aims to provide a comprehensive and up-to-date chronological review of studies on the mechanical performance of asphalt mixtures—primarily hot mix asphalt (HMA)—incorporating recycled concrete aggregate (RCA). Since the main limitation of RCA is the presence of residual adhered mortar, the review also includes studies that applied various surface treatments (mechanical, chemical, and thermal, among others) to enhance mixture performance. The article summarizes the experimental procedures used and highlights the key findings and conclusions of the reviewed research. Although the results are varied and sometimes contradictory—mainly due to the source variability and heterogeneity of RCA—the use of these materials is technically viable. Moreover, their application can provide environmental, social, and economic advantages, particularly in the construction of low-traffic roadways. Finally, the article identifies research gaps and offers recommendations for future researches.

Keywords: recycled concrete aggregates; RCA; hot mix asphalt; stone mastic asphalt; semi-dense asphalt

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1. Introduction

1.1. Problem Statement

Construction and demolition waste (CDW) consists of discarded by-products generated from construction, renovation, and demolition activities of civil infrastructure. CDW is primarily composed of concrete, mortar, glass, ceramics, bricks, tiles, plastics, soil, reclaimed asphalt pavement (RAP), and gypsum, among others (See Figure 1) [1–3]. Globally, it is estimated that more than 10 billion tons of CDW exist [4]. In China, approximately 2.36 billion tons of CDW were reported between 2003 and 2013 [5]; however, by 2021, this numeral had increased to 3.04 billion tones [6]. In that country, CDW accounts for around 40% of total solid waste generation [7]. In India, according to the Centre for Science and Environment, approximately 150 million tons of CDW were generated in 2020 [8]. In 2022, the European Union [9] reported the generation of approximately 858.6 million tons of CDW, representing 38.4% of total solid waste. The main contributors were Germany, the United Kingdom, France, Italy, and the Netherlands. Australia reported the generation of approximately 29 million tons of CDW in 2021, accounting for 38% of its total solid waste [10]. In the United States, CDW generation in 2018 reached approximately 600 million tons, with about 90% attributed to demolition activities and the remaining 10%

to construction [11]. In Latin America, Brazil reported an estimated 45 million tons of CDW in 2015, representing 57% of total solid waste [12]. This number increased to 48 million tons by 2021 [13]. In Chile, CDW generation reached approximately 7.2 million tons in 2021, accounting for 34% of the country's total solid waste [14]. In Colombia, data from the Ministry of Environment and Sustainable Development indicated that approximately 22.3 million tons of CDW were generated in 2011 [15]. Uruguay was estimated to produce 450,000 tons of CDW in 2019 [16]. In countries such as Argentina, Ecuador, Bolivia, Peru, Venezuela, and Paraguay, no official figures on CDW generation were found. In Mexico, between 2006 and 2012, CDW generation was reported at approximately 6.1 million tons per year. However, this amount increased significantly, reaching 18.5 million tons in Mexico City alone by 2022 [17].

Figure 1. Construction and demolition waste: (**a**) CDW, (**b**) CDW aggregate.

The lack of proper management of CDW can lead to several environmental issues, including contamination of water sources, changes in land use, and reduced lifespan of landfills and designated disposal sites [18–20]. As a result, various studies have explored the use of CDW as a substitute material for natural aggregate (NA) in the production of hot mix asphalt (HMA) for pavement construction, aiming to mitigate the environmental impacts associated with the extraction of NA [21,22] (See Figure 2). Other applications of CDW include its use in concrete production [23–27], granular pavement layers [28–30], and prefabricated construction elements [31,32], among others. Concrete and mortar waste can account for approximately 40% to 75% of total CDW [1], and these materials can be crushed and processed into recycled concrete aggregate (RCA) [1,33]. RCA typically consists of two main components: adhered mortar and original NA (See Figure 2) [2,34]. While there are few studies reporting reliable and precise figures on RCA generation, the United States reported approximately 455 million tons of CDW processed for recycling in 2018 [11]. In Japan, nearly 98% of RCA is processed and reused as construction aggregates [33]. The recycling rates of CDW in Australia, the United States, and Norway are approximately 67%, 45%, and 41%, respectively [35]. The properties of RCA are primarily influenced by the adhered mortar, cement quality, type of NA, and source of the waste, among other factors [27,33,36].

The main advantages of using RCA in HMA production lie in their shape and cleanliness characteristics. RCA typically exhibits a cubic shape, resulting from the crushing and size reduction processes involved in recycling, which contributes to improved particle interlocking and enhanced stiffness of the HMA [37]. Microscopic images have shown that RCA has a higher surface roughness compared to NA, primarily due to the presence of adhered mortar [2,38]. Additionally, RCA generally meets the cleanliness requirements for HMA production; however, washing and drying are recommended to remove fine particles that could negatively affect asphalt adhesion [39]. The main disadvantages of RCA in hot mix asphalt (HMA) lie in the adhered mortar, which is characterized by low density, high porosity, and a tendency to detach and fracture easily due to its brittleness [40,41], as well as the need for a higher asphalt content. The adhered mortar accounts for approximately 30% to 35% of the total mass of RCA [42], which may lead to higher wear in tests such as the Los Angeles abrasion test, the micro-Deval test, and the soundness test.

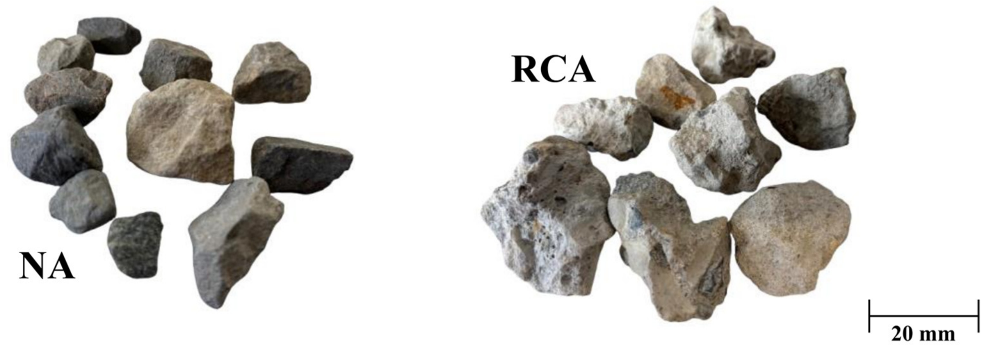

Figure 2. Aggregates.

The mechanical performance of asphalt mixtures containing RCA varies significantly due to differences in the origin, source, and physical and mechanical properties of the RCA. Some studies report that such mixtures meet the necessary specifications for asphalt production, particularly for low-traffic road applications. Additionally, several studies have observed improvements in resistance to monotonic loading (Marshall stability) and repeated loading (rutting and fatigue resistance). However, contrasting results have also been reported in the literature. To better understand the influence of RCA on asphalt mixtures, a review of the relevant literature was conducted, identifying six notable studies on the topic [37,43–47]. Cardoso et al. reported on various CDW applications in geotechnical engineering, with an emphasis on pavement use, including RCA-based applications, recycled masonry aggregate (RMA), mixed recycled aggregate (MRA), reclaimed asphalt pavement (RAP), and construction and demolition recycled aggregate (CDRA) [44]. However, their study does not address the mechanical behavior of asphalt mixtures containing RCA. Tang et al. [48] discuss changes in the physical and chemical properties of RCA subjected to surface treatments aimed at reducing the amount of adhered mortar (mechanical grinding, heating, thermo-mechanical, chemical, and microbial precipitation). Additionally, a summarized overview is presented on the influence of RCA—both untreated and treated—on the key properties of HMA (volumetric properties, high and low temperature stability, water stability, and fatigue life) [48]. Other studies have analyzed the physical, chemical, and mechanical properties of RCA. They also report on the mechanical performance of mixtures containing RCA, including resistance to monotonic loading, moisture susceptibility, rutting, fatigue, and low-temperature cracking [37,43,45–47]. However, these manuscripts provide limited descriptions.

1.2. Research Objectives

The previous literature reviews do not provide detailed information on key methodological aspects such as the type of asphalt binder, RCA content, or the substitution method (by mass or volume), among others. Moreover, these reviews only report studies published up to the year 2022. Therefore, the main objectives of this article are as follows:

- To present a broader, more detailed, and up-to-date chronological review of the state of knowledge regarding the use of recycled concrete aggregate (RCA) in the production of asphalt mixtures, primarily hot mix asphalt (HMA), aiming to contribute to the general understanding of RCA utilization in HMA.

- To highlight studies that have applied surface treatments to RCA (e.g., mechanical, thermal, and others) and their incorporation into asphalts mixtures production.
- To provide recommendations and propose potential research directions for future investigations on the use of RCA in asphalt mixtures.

It should be noted that this study does not consider research related to the use of RCA in granular pavement layers or other geotechnical applications. The documents analyzed correspond to articles published in high-impact journals classified within Q1, Q2, Q3, and Q4 categories according to the SCOPUS and SCIMAGO bibliographic databases. The information presented in this article serves as a valuable reference for researchers developing projects in this field. Furthermore, it contributes to advancing the discussion regarding the potential use of RCA in asphalt mixtures for pavement applications. This manuscript includes a detailed methodological description of the study (Section 2), followed by a chronological presentation of the review results on the use of RCA in asphalt mixtures, both untreated and pretreated (Sections 3 and 4, respectively). Finally, the review findings are discussed (Section 5), and conclusions and recommendations are provided (Section 6).

2. Materials and Methods

The state-of-the-art review was conducted based on documents published by the American Society of Civil Engineers (ASCE) and scientific databases including MDPI, Google Scholar, Scopus, Web of Science, ScienceDirect, Taylor & Francis, and SpringerLink, among others. The literature search employed keywords such as "asphalt mixture," "recycled concrete aggregate," "RCA," "construction and demolition waste," "CDW," "mechanical properties," "Marshal properties," "natural aggregate," "NA," "moisture susceptibility," "indirect tensile strength," "resilient modulus," "stiffness modulus," "fatigue", and "permanent deformation."

Articles related to asphalt mixtures incorporating RCA were reviewed and analyzed for the period from 2006 to 2025, totaling 77 publications. The articles were categorized into two groups: (i) Use of RCA in asphalt mixtures without treatment; (ii) Surface treatments of RCA (mechanical, chemical, and thermal, among others) for use in asphalt mixtures. These studies mainly focus on the use of RCA in hot mix asphalt (HMA), although other types of hot asphalt mixtures are also considered, such as stone mastic asphalt (SMA), dense bituminous macadam (DBM), and semi-dense asphalt (SDA), which corresponds to a dense-graded mixture. For each article, a general description was provided, addressing the following questions: What did the authors do? How did they do it (methodology)? What are the results and conclusions? Additionally, to facilitate understanding and comparison, a summary database was created presenting information such as the type of asphalt binder used, RCA fraction (coarse, fine, or combined), percentage of RCA relative to the fraction used, and particle sizes of RCA. Mixture design methods (Marshall and Superpave, among others) were identified, reporting their effects on optimum asphalt content (OAC) and air voids in comparison to the control mixture (without RCA). Mechanical properties were evaluated based on resistance to monotonic loading (Marshall stability, indirect tensile strength), moisture susceptibility, stiffness (resilient or dynamic modulus), resistance to rutting, and fatigue, all relative to the control mixture. For studies involving surface treatments of RCA, the analysis considered comparisons against both the control mixture and untreated RCA.

During the description of the studies, wt% refers to the percentage by weight, NA indicates natural aggregate, RCA indicates recycled concrete aggregate, HMA indicates hot mixture asphalt, DBM denoted dense bituminous macadam, SDA refers to semi-dense asphalt, NMAS refers to nominal maximum aggregate size, SMA refers to stone mastic asphalt, SGC refers to Superpave gyratory compactor, ESAL indicates equivalent single axle load, AC refers to asphalt cement, CRMA denotes crumb rubber modified asphalt, AH denotes asphalt hard, PG refers to performance grade, VG indicates viscosity grade, OAC indicates optimum asphalt content, Av refers to air void, VTM indicates void total mixture, VFA denotes voids filled with asphalt, S refers to stability Marshall, F refers to flow Marshall, ITS refers to indirect tensile stress, TSR refers to tensile strength ratio, RM indicates resilient modulus, and ML indicates mass loss.

3. Overview of RCA in Asphalt Mixtures

A summary of the review is shown in Table 1.

The following section presents the reviewed manuscripts in chronological order.

Paranavithana et al. [40] produced two asphalt mixtures by replacing 100 wt% of the coarse fraction of NA with RCA (53%, particle size between 4.75 mm and 20 mm). Specimens were compacted using 80 and 120 gyrations in the SGC, with asphalt contents of 5.0%, 5.5%, 6.0%, and 6.5%. Subsequently, RM and permanent deformation tests were conducted at 50 °C to evaluate the stiffness of the mixtures. The results indicated a decrease in RM for the mixtures containing RCA, possibly due to the increase in Av and the fracture of RCA particles during the compaction process. However, the results remained within the acceptable range established by the Austroads Pavement Research Group for asphalt mixtures. Additionally, permanent deformation results at 50 °C showed similar values for both mixtures. Therefore, the authors concluded that the use of RCA in asphalt mixtures is technically feasible.

Mills-Beale et al. [49] developed HMA using PG 64-34 asphalt by replacing 0%, 25%, 35%, 50%, and 75 wt% of NA (particle size between 0.0 mm and 19 mm) with RCA. The control HMA mix design (0% RCA) was carried out according to the Superpave methodology for low traffic volume conditions (between 0.3 and 1.0 million ESALs), resulting in an OAC of 5.6%. To evaluate the performance of the mixtures, ITS, TSR, dynamic modulus, and rutting resistance tests were conducted. The results indicated that HMAs with RCA exhibited lower values of ITS, TSR, dynamic modulus, and rutting resistance compared to the control HMA. Higher RCA contents led to a deterioration in the performance of the asphalt mixture. Although the experimental campaign was extensive, including repeated load tests, the authors did not assess the influence of OAC in HMA with RCA, which could potentially improve RCA coating and, consequently, the mechanical performance of the mixtures.

Bhusal et al. [50] produced HMA using PG 58-28 asphalt by replacing 20%, 40%, 60%, 80%, and 100 wt% of NA with RCA (particle size between 0.0 mm and 19 mm). The mixture designs followed the Superpave methodology for roads with low traffic volumes (between 0.3 and 1.0 million ESALs). The results indicate that the OAC increased with RCA content, ranging from 6.8% to 9.2%, and the effective asphalt content varied between 4.45% and 4.81%, reflecting the high absorption capacity of RCA. The study did not report reference values for the control HMA (0% RCA). The authors concluded that RCA can be used for HMA production in low-traffic applications, as the mixtures met the requirements established in the state of Washington, United States. However, they recommended further testing for fatigue resistance, rutting, thermal cracking, and moisture susceptibility since only volumetric parameters were evaluated.

Table 1. Summary of studies on asphalt mixtures incorporating RCA.

Author	Asphalt Binder	Mixture	RCA (%)	Fraction	Size (mm)	Compaction	OAC	Av	S	ITS	TSR	Stiffness	Resistance to	
													Rutting	Fatigue
[40]	NS	HMA	0, 50 wt	C	4.75 to 20	Superpave	---	I	---	---	---	D	S	---
[49]	PG 64-34	HMA	0, 25, 35, 50, 75 wt	C-Fi-Filler	0.0 to 19	Superpave	---	I	---	D	D	D	D	---
[50]	PG 58-28	HMA	0, 20, 40, 60, 80, 100 wt	C-Fi-Filler	0.0 to 19	Superpave	I	Si	---	---	---	---	---	---
[51]	PG 64-22	HMA	0, 40, 60, 100 wt	Fi-Filler	0.0 to 4.75	Marshall	I	Si	Si	I	I	---	I	---
				C	4.75 to 25		I	Si	Si	I	I	---	I	---
				C-Fi-Filler	0.0 to 25		I	Si	Si	D	D	---	D	---
[20]	AC 60-70	HMA	0, 25, 50, 75 wt	C-Fi-Filler	0.0 to 19	Marshall	I	I	D	---	---	---	---	---
				C-Fi-Filler	0.0 to 25		I	I	D	---	---	---	---	---
[1]	AC 60-70	HMA	0, 41, 53 wt	Fi	0.075 to 4.75	Marshall	I	D	I	---	---	I	I	I
				C	4.75 to 19		I	I	D	---	---	D	D	D
[52]	AC 60-70	HMA	0, 6, 41, 53, 100 wt	C	4.75 to 19	Marshall	I	Si	D	---	---	D	D	D
				Fi	0.075 to 4.75		I	Si	I	---	---	I	I	I
				Filler	0 to 0.075		Si	Si	I	---	---	I	I	I
				C-Fi	0.075 to 19		I	Si	D	---	---	D	D	D
[53]	AC 60-70	HMA	0, 10, 20, 30, 40 wt	C-Fi-Filler	0.0 to 12.5	Marshall	I	I	D	---	---	D	I	---
[54]	AC 50-70	HMA	0, 25, 50, 75 wt	C-Fi-Filler	0.0 to 12	Marshall	I	I	---	---	---	---	D	---
				C-Fi-Filler	0.0 to 19		I	D	---	---	---	---	I	---
[55]	AC 50-70	HMA	0, 10.5, 21, 31.5, 42 wt	C	4.75 to 19	Marshall	I	I	D	---	D	---	I	---
[56]	AC 40-50	HMA	4, 8, 12, 16, 20, 24, 28, 32, 36, 40 wt	C	4.75 to 37.5	Marshall	----	I	I	I	---	---	---	---
[57]	AC 60-70, AC 80-100	HMA	0, 11.75, 28.20, 37.60, 47 wt	C	4.75 to 19	Superpave	I	I	D	D	D	D	---	---
[58]	AC 35-50, CRMA	HMA	0, 35, 42 wt	C-Fi-Filler	0.0 to 22.4	Marshall	I	I	---	D	I	---	---	---
[58]	AC 35-50 CRMA	HMA	0, 35, 42 wt	C-Fi-Filler	0.0 to 22.4	Marshall	I	I	---	---	I	---	---	I
[59]	AC 50-70	HMA	0, 6.3, 12.6, 18.9 wt	Fi-Filler	0.075 to 4.0	Marshall	I	I	I	---	---	D	D	---
			0, 8.7, 17.4, 26.1 wt	C	4.0 to 22.4	Marshall	I	I	I	---	---	D	I	---
			0, 15, 30, 45 wt	C-Fi-Filler	0.0 to 22.4	Marshall	I	I	I	---	---	D	D	---
[60]	AC 60-70	HMA	0, 50 wt	Fi-Filler	0.0 to 4.75	Marshall	---	---	---	---	---	---	---	---
			0, 50 wt	C	4.75 to 19	Marshall	---	---	---	---	---	---	---	---
[61]	AC 50-70	HMA	0, 100 wt	C-Fi-Filler	0.0 to 19	Marshall	I	I	I	I	I	D	I	D
	CRMA		0, 100 wt	C-Fi-Filler	0.0 to 19	Marshall	I	I	I	I	D	D	I	D

Table 1. *Cont.*

Author	Asphalt Binder	Mixture	RCA (%)	Fraction	Size (mm)	Compaction	OAC	Av	S	ITS	TSR	Stiffness	Resistance to	
													Rutting	Fatigue
[62]	AC 50-70	HMA	0, 11, 22, 33 wt	C	4.75 to 22	Marshall	---	I	---	I	D	---	---	---
[63]	AC 50-70	HMA	0, 9, 18, 27, 36 wt	C	5 to 13	Marshall	I	I	I	D	I	D	I	---
[64]	VG 30	DBM	0, 100 wt	C	4.75 to 37.5	Marshall	I	I	I	D	D	D	---	---
[65]	AC 60-70	HMA	0, 6.45, 12.90, 19.35 wt	C	4.75 to 19	Marshall	I	I	D			I		---
[66]	AC 50-70	HMA	0, 15, 30, 45 wt	Fi	0.075 to 4.0	Marshall	I	I	---	---	---	D	---	I
				C	4.0 to 22.4	Marshall	I	I	---	---	---	D	---	I
				C-Fi	0.075 to 22.4	Marshall	I	I	---	---	---	D	---	I
[39]	Modified Asphalt	SDA	0, 7, 12, 24, 32, 64 wt	Fi	2.0 to 4.0	Superpave	I	I	---	I	D	---	I	---
				Fi	0.125 to 2.0	Superpave	Si	I	---	I	D	---	I	---
				Filler	0.00 a 0.075	Superpave	Si	Si	---	Si	D	---	Si	---
[67]	AC 80-100	SMA	0, 20, 40, 60, 80, 100 wt	C	4.75 to 12.5	Marshall	I	I	I	I	I	I	I	I
				C-Fi	0.075 to 12.5	Marshall	I	I	I	D	I	D	D	I
[68]	AC 60-70	HMA	0, 6.45, 12.90, 19.35 wt	C	4.75 to 19	Marshall	I	I	---	D	D	I	---	---
[69]	AC 60-70	HMA	0, 43, 51, 94 wt	Fi	0.075 to 4.75	Marshall	I	I	Si	I	---	---	---	---
				C	4.75 to 19		I	I	Si	I	---	---	---	---
				C-Fi	0.075 to 19		I	I	D	----	---	---	---	---
[70]	AC 32	HMA	0, 10.5, 21 wt	C	4.75 to 19	Marshall	I	I	----	---	---	---	---	---
[71]	AC 60-70	HMA	0, 12.5, 21 wt	C	12.5 to 19	Marshall	I	I	I	I	D	I	I	I
				C	9.5 to 19		I	I	I	I	D	I	I	I
		HMA	0, 12.5, 21v	C	12.5 to 19		I	D	I	I	D	I	D	I
				C	9.5 to 19		I	I	I	I	D	I	I	I

Note: No Specific (NS); Increase (I); Decrease (D); Similarly (Si); Coarse (C); Fine (Fi).

Cho et al. [51] prepared asphalt base mixtures by replacing 0%, 40%, 60%, and 100% of the fine–filler, coarse, and coarse–fine–filler fractions of NA with RCA, using PG 64-22 binder. The particle size ranges for the fine–filler, coarse, and coarse–fine–filler fractions were 0.0–4.75 mm (40%), 4.75–25 mm (60%), and 0.0–25 mm, respectively. The Marshall test was conducted to determine the OAC, ensuring Av = 5.0 ± 0.5%. Subsequently, ITS and rutting resistance were evaluated using the Kim test and the wheel tracking test. The Marshall test results indicated that the mixtures with RCA met the specifications used for base layers in South Korea; however, OAC increased. In addition, ITS and rutting resistance improved in mixtures with RCA in the fine and coarse fractions compared to the control mixture (100% NA). Nevertheless, the mixture with coarse–fine RCA exhibited worse performance than the control.

Rafi et al. [20] designed asphalt mixtures using the Marshall method by replacing 0%, 25%, 50%, and 75 wt% of the NA fraction with RCA, employing AC 60-70. Two gradations were used, referred to as coarse (particle size between 0.0 mm and 25 mm) and fine (particle size between 0.0 mm and 19 mm). In general, the OAC increased with the RCA content for both types of mixtures, with higher OAC values observed for the fine mixtures. Regarding Marshall stiffness (defined as S/F ratio), both gradations showed a decrease in stiffness as RCA content increased. The authors concluded that mixtures with up to 50% RCA comply with the required parameters to produce asphalt mixtures for road pavements in Pakistan. However, the study presents a limited experimental phase, as it only evaluated parameters from the Marshall test.

Arabani et al. [1] evaluated the performance of an HMA by replacing the fine (53% of total aggregates, particle size between 0.0075 mm and 4.75 mm) and coarse (41% of total aggregates, particle size between 4.75 mm and 19 mm) fractions of NA with RCA, using AC 60-70 in accordance with the specifications for asphalt mixture production in Iran. Marshall test, dynamic creep, and fatigue resistance tests were conducted. The results indicated an increase in OAC for both mixtures compared to the control HMA (0% RCA). The HMA with fine RCA exhibited lower Av, which increased S, permanent deformation resistance, and fatigue resistance under strain-controlled conditions. The HMA with coarse RCA showed the opposite behavior. The authors concluded that during compaction, the fine RCA particles fracture, forming a denser granular skeleton that enhances mixture stiffness due to the presence of residual cement.

Ektas et al. [53] produced SMA mixtures by replacing 0%, 10%, 20%, 30%, and 40 wt% of NA (coarse–fine–filler fraction, particle size between 0.0 mm and 12.5 mm) with RCA, using AC 60-70. The Marshall test was conducted in accordance with Turkish construction specifications. Additionally, RM and dynamic creep tests at 40 °C were performed to assess mechanical performance. The results indicated a slight decrease in OAC for mixtures with 10% and 20% RCA compared to the control mixture (0% RCA); however, OAC increased for mixtures with 30% and 40% RCA. In general, RCA increased Av, resulting in lower S compared to the control. RM decreased as RCA content increased, although the mixture with 10% RCA exhibited higher stiffness than the control. Dynamic creep results indicated greater rutting resistance in RCA mixtures compared to the control, demonstrating adequate RCA performance at 40 °C. Based on the laboratory results, an artificial neural network (ANN) model was used to estimate RM in SMA mixtures with RCA. The results yielded a coefficient of determination of 0.98, indicating strong agreement with the experimental data.

Arabani et al. [52] evaluated the performance of an HMA by replacing the coarse, fine, filler, and total fractions of NA with RCA. AC 60-70 was used as the binder. The coarse, fine, and filler fractions accounted for 41%, 53%, and 6% of the total aggregates, respectively. Marshall, RM, rutting resistance, and fatigue resistance tests (under strain-controlled conditions) were conducted. According to the results, OAC increased for the mixtures containing RCA, except for the HMA with 6 wt% RCA (filler). Regarding mechanical behavior, the mixtures in which the fine and filler fractions of NA were replaced with RCA exhibited higher S, RM, rutting resistance, and fatigue performance compared to the control mixture. In contrast, mixtures with 100% RCA and those replacing the coarse fraction showed inferior performance. The authors suggested that the reduction in Av, caused by the fracture of fine particles during compaction, may have led to increased mixture stiffness due to the internal arrangement of these particles.

Gul and Guler [52,54] produced asphalt mixtures by replacing 0%, 25%, 50%, and 75 wt% of the NA fraction with RCA, using AC 50-70. Mixtures were prepared with two different gradations, referred to as fine and coarse. The particle size ranges of the RCA fractions were 0.0–12.5 mm (fine) and 0.0–19 mm (coarse). Permanent deformation tests were conducted at 50 °C to simulate pavement conditions in Turkey. Additionally, a compressive stress of 350 kPa and a loading frequency of 10 Hz were applied over 10,000 cycles. In mixtures with NA (0% RCA), the fine gradation exhibited greater rutting resistance than the coarse one, which was attributed to its lower OAC. These findings were contrary to expectations since coarse mixtures typically require less asphalt than fine mixtures due to their lower aggregate surface area. Consequently, rutting resistance decreased with increasing RCA content in the fine mixtures. In contrast, the opposite trend was observed when RCA was used in the coarse asphalt mixtures.

Motter et al. [55] used 25%, 50%, 75%, and 100 wt% of RCA (coarse fraction, particle size between 4.75 mm and 19 mm) as a substitute for NA in the production of an HMA. The coarse fraction represented 42% of the total aggregates. Marshall, rutting resistance, and TSR tests were conducted. The results showed that both Av and OAC increased with the RCA content. Additionally, the mixtures containing RCA exhibited lower S and TSR compared to the control mixture. However, rutting resistance increased, which was attributed to the higher OAC—except in the case of the mixture with 100% RCA.

Razzaq [56] used RCA to replace 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, and 100 wt% of the coarse fraction of NA (representing 40% of the total aggregates, with particle sizes between 4.75 mm and 37.5 mm), employing AC 40-50. The Marshall test was used to design the control mixture (0% RCA). Based on the resulting OAC, RCA mixtures were prepared and evaluated using Marshall parameters (VTM, VFA, S, and F) to determine the optimal RCA content in the mixture, which was established at 58% (maximum value extrapolated from the S curve). Subsequently, the influence of NMAS was assessed using 37.5 mm, 25 mm, and 19 mm, and results generally indicated that mixtures with a 19 mm NMAS provided higher ITS compared to the control mixture. Although a wide range of RCA contents was tested, the study only evaluated monotonic loading; no tests were conducted to assess the dynamic performance of the asphalt mixtures.

Qasrawi et al. [57] evaluated the performance of HMAs produced with AC 60-70 and AC 80-100 by replacing 0%, 25%, 50%, 75%, and 100 wt% of the coarse fraction of NA with RCA (47% of total aggregates, particle size between 4.75 mm and 19 mm). The Superpave methodology was used for mixture design, applying a target Av of 4.0%. ITS, TSR, and RM tests were performed. Additionally, skid resistance was assessed to evaluate the surface texture of the pavement layer. The results showed that both Av and OAC increased with RCA content. Mechanical performance results indicated that S, ITS, TSR, and RM decreased as RCA content increased. Better overall performance was observed with AC 60-70 due to its higher stiffness and viscosity. The authors concluded that RCA content in HMA should not exceed 25% in order to ensure adequate strength and durability. Furthermore, the inclusion of RCA improved skid resistance due to the rough surface texture of the particles.

Pasandín and Pérez [58,72] investigated the water susceptibility (TSR) and fatigue resistance (strain-controlled) of HMA by incorporating 0% (control), 35%, and 42 wt% of RCA as a substitute for NA (particle size between 0.0 mm and 22.4 mm), using AC 35-50 (penetration grade) and CRMA. The results indicated that the volumetric composition of the mixtures met the technical specifications for road and bridge construction in Spain. Moreover, both TSR and fatigue resistance increased in the RCA mixtures compared to the control, regardless of the asphalt type. The highest values of TSR and fatigue resistance were observed in mixtures with 35% and 42% RCA combined with CRMA. This behavior was mainly attributed to the use of the modified binder and the similarity of Av compared to the control mixture.

Radevic et al. [59] produced HMAs by replacing 0% (control), 15%, 30%, and 45 wt% of NA with RCA using AC 50-70. The fine (0.075 mm to 4.0 mm), coarse (4.0 mm to 22.4 mm), and fine–coarse–filler fractions (0.0 mm to 22.4 mm) were replaced. The fine and coarse fractions accounted for 42% and 58% of the total aggregates, respectively. Marshall, dynamic modulus (at 5 °C, 15 °C, and 25 °C), and permanent deformation tests were conducted. Overall, the results indicated that HMAs with RCA exhibited higher OAC and S compared to the control mixture. However, the dynamic modulus slightly decreased at all tested temperatures. Regarding rutting resistance, a slight improvement was observed when replacing the coarse fraction with RCA, whereas the use of the fine and fine–coarse fractions resulted in the opposite trend.

El-Tahan et al. [60] used RCA derived from new concrete (employed for quality control testing during construction) and from old demolished buildings to produce asphalt mixtures by replacing NA. Both full replacement (particle size between 0.0 mm and 19 mm) and replacement of the coarse aggregate fraction (50% of total aggregates, particle size between 4.75 mm and 19 mm) were performed. The mixtures were produced using AC 60/70. Marshall, ITS (dry/wet), and TSR tests were conducted to evaluate mechanical performance. However, the authors did not include a control mixture (0% RCA). The results indicated that new RCA showed higher surface absorption, leading to increased OAC in the mixture. In general, all mixtures met the requirements for pavement layer construction in Egypt. The best performance was observed in mixtures using RCA sourced from new concrete.

Muniz et al. [61] investigated the incorporation of 0% (control) and 100 wt% of RCA as a replacement for NA (particle size between 0.0 mm and 19 mm) in the production of HMA. Two asphalt binders were used: AC 50/70 and a CRMA-modified binder. Marshall, ITS, TSR, RM, rutting resistance, and strain-controlled fatigue tests were performed. The results showed higher OAC in mixtures containing RCA and CRMA. S, S/F, and ITS increased with RCA compared to NA, regardless of the asphalt type. However, RM, rutting resistance, and fatigue performance decreased. In terms of durability (evaluated by TSR), an increase was observed with AC 50/70, while a decrease occurred with CRMA.

Galán et al. [62] replaced 0%, 20%, 40%, and 60 wt% of RCA (coarse fraction, representing 55% of the total aggregates, particle size between 4.75 mm and 22 mm) with NA in the production of HMA using AC 50-70. Two sources of NA were evaluated: (i) shale and (ii) calcite–dolomite. Response surface methodology was used to analyze the ITS and TSR of the mixtures. The results indicated that to meet the TSR specifications for construction in Spain, the optimal RCA content was approximately 11% and 17% when using calcite–dolomite and shale NA, respectively. Better performance was observed when RCA was combined with calcite–dolomite NA, attributed to the presence of quartz. However, the authors did not report the asphalt contents used in the mixtures.

Álvarez et al. [63] investigated the incorporation of 20%, 40%, 60%, and 80 wt% of RCA (50% of total aggregates, particle size between 5 mm and 13 mm) as a replacement for

NA in an HMA. Marshall, ITS, TSR, RM, and rutting resistance tests were performed. The results showed that OAC, Av, S, F, and S/F increased with RCA content. ITS under dry and wet conditions increased (except at 80% RCA) and decreased, respectively, compared to the control mixture, resulting in an overall increase in TSR with RCA content. Additionally, RM decreased with RCA content, whereas rutting resistance increased.

Sanchez-Cotte et al. [68] studied coarse RCA (particle size between 19 mm and 4.75 mm, accounting for 43% of the total aggregates) sourced from two different origins—buildings and road pavements—for use in HMA with AC 60-70. RCA was incorporated at 15%, 30%, and 45 wt% relative to the coarse fraction of the HMA. Marshall, ITS, TSR, and RM tests were performed. The results showed reductions in S/F, ITS, and TSR, although RM increased. Better performance was observed in mixtures incorporating RCA from road pavement waste.

Radevic et al. [66] conducted replacements of 0%, 15%, 30%, and 45 wt% of the fine (0.075 mm to 4 mm), coarse (4.75 mm to 22.4 mm), and combined fine–coarse (0.075 mm to 22.4 mm) NA fractions with RCA for the production of HMA using AC 50-70. The fine and coarse fractions represented 42% and 58% of the total aggregates, respectively. Marshall, RM, fatigue resistance, and low-temperature cracking tests were performed to assess performance. Results indicated that RCA incorporation increased the OAC. Strain-controlled fatigue resistance improved by 12% to 26% compared to the control mixture, as reflected in the increase of the $\varepsilon 6$ parameter (strain amplitude at failure after one million cycles), which was attributed to the higher OAC. In general, mixtures with RCA exhibited lower dynamic modulus and reduced resistance to low-temperature cracking compared to the control mixture.

Gopalam et al. [64] conducted a full replacement of the coarse fraction (54% of the total aggregates, particle size between 4.75 mm and 37.5 mm) of NA with RCA to produce an HMA. In addition, four types of fillers were used: cement, stone dust, fly ash, and carbon black. Marshall, ITS, TSR, and RM tests were performed to assess the mechanical behavior of the HMA. The results indicated that HMA with RCA exhibited reduced Av, which led to increased Marshall stiffness (S/F). However, ITS, TSR, and RM values decreased. The best performance was observed when cement was used as the filler in the HMA.

Mikhailenko et al. [39] performed partial and full replacement of the fine (particle size between 0.125 mm and 2.0 mm) and coarse (particle size between 2.0 mm and 4.0 mm) NA fractions with RCA for the production of a semi-dense asphalt mixture using SBS-modified asphalt (styrene–butadiene–styrene). Additionally, the NA filler was replaced with RCA. The coarse, fine, and filler fractions accounted for 63%, 24%, and 7% of the total mixture, respectively. The mixtures were designed using the Superpave methodology and the Swiss pavement construction specifications. The results showed that the OAC in the RCA mixtures was equivalent to that of the NA mixture, except when the coarse fraction was replaced with RCA. ITS increased with RCA replacement, but also indicated greater brittleness in terms of crack initiation and propagation resistance, which may explain the observed reduction in TSR. Rutting resistance increased in mixtures with RCA fine and coarse fractions compared to the control, but similar behavior was observed when RCA was used as filler.

Vega et al. [65] used 0%, 15%, 30%, and 45 wt% of RCA (particle size between 4.75 mm and 19 mm) to replace the coarse fraction of NA in an HMA with AC 60-70. The coarse fraction accounted for 43% of the total aggregates. Marshall and RM tests were conducted to evaluate the performance of the HMA. The results indicated that OAC and Av increased with RCA content. S decreased in HMAs with 15% and 30% RCA compared to the control mixture (0% RCA). However, RM increased for these mixtures and decreased for the mixture with 45% RCA. The authors did not extensively discuss the mechanical behavior of the mixtures with RCA, as the primary objective of the study was to quantify environmental impacts throughout the pavement life cycle.

Nwakaire et al. [67] evaluated SMA mixtures with 20%, 40%, 60%, 80%, and 100 wt% replacement of the coarse fraction of NA (68.5% of total aggregates, 4.75–12.5 mm) by RCA using AC 80-100. An additional HMA with RCA replacing the coarse–fine fraction (0.075–19 mm) was also analyzed. Marshall, ITS, TSR, RM, rutting resistance, Cantabro abrasion, skid resistance, and fatigue tests were conducted. Results showed that RCA increased OAC and Av. The best mechanical performance under compressive loading was observed at high RCA contents, whereas indirect tensile strength and fatigue resistance improved at 20–40% RCA. The HMA with coarse–fine RCA exhibited higher S, TSR, and abrasion resistance, but lower ITS, rutting, and skid resistance. The authors recommend 40% RCA content as optimal for Malaysian specifications.

Bastidas et al. [69] produced three mixtures by replacing the coarse (particle size between 19 mm and 4.75 mm), fine (particle size between 4.75 mm and 0.075 mm), and total fractions of NA in an HMA using AC 60-70. The coarse and fine fractions represented 43% and 51% of the total aggregates, respectively. Marshall, ITS, and Cantabro ML tests were conducted according to Colombian specifications for road construction. The results indicated that the OAC increased in the mixtures with RCA. Likewise, a reduction in S and S/F was observed, along with an increase in ITS and ML. The authors concluded that the HMA with replacement of the coarse RCA fraction (21 wt% with respect to the total mass) exhibited the best performance.

Tahmoorian et al. [70] evaluated the behavior of a mixture by replacing 0%, 25%, and 50 wt% of the coarse NA fraction (basalt, 42% of total aggregates, particle size between 4.75 mm and 12.5 mm) with RCA, using AC 32 for heavy traffic levels in warm climates in Australia. The Marshall test was used to evaluate the performance of the asphalt mixtures. Similar to other studies, the results indicated that Av and OAC increased with RCA. The authors concluded that mixtures with 20% to 22% RCA meet the requirements of Australian specifications. However, the study is limited, as it only evaluated the volumetric composition of the mixtures without considering their mechanical performance.

Sejin et al. [71] conducted partial replacements of the coarse fraction of NA with RCA for the production of an HMA using AC 60-70. Two RCA particle size intervals were analyzed, namely, between 19 mm and 12.5 mm and between 19 mm and 9.5 mm, which represented 12.5 wt% and 21 wt% of the total aggregate content, respectively. The replacement was performed by mass and by volume. The mixture designs were carried out following the Marshall methodology. Subsequently, ITS, TSR, RM, permanent deformation, and fatigue resistance under controlled stress tests were conducted. Additionally, the Cantabro test was performed to measure abrasion and raveling resistance. The results of the Marshall test met the volumetric and strength parameters established by the Colombian specifications (particularly for low-traffic roads). RCA increased both Av and OAC; however, replacement by volume could help reduce the OAC. Mixtures with RCA exhibited better mechanical performance in all tests conducted; however, moisture damage resistance could be compromised when volumetric dosing is used and the asphalt content is reduced. In general, replacement by mass or volume did not produce clear trends in the results, but an overall better performance was reported in mixtures dosed by volume.

4. Surface Treatments on RCA

RCA is characterized by high surface absorption and lower mechanical strength compared to NA, which is attributed to the adhered mortar coating on the particles. This condition is unfavorable for the production of asphalt mixtures, as it results in an increase in the OAC [42,73]. Therefore, several studies have been conducted with the objective of applying surface treatments to RCA in order to reduce surface absorption and improve their mechanical performance in asphalt mixtures. Table 2 presents studies on asphalt mixtures incorporating surface-treated RCA, using thermal, mechanical, chemical (material addition), biological, and other treatment procedures.

Table 2. Constituent materials of the asphalt mixtures studied and surface-treated RCA.

Author	Mixture	Asphalt Binder	Treatment	RCA (%)	Fraction	Size (mm)
[74]	HMA	AC 60-70	Thermal	0, 6, 45 wt	Filler	0 to 0.075
					Filler-Fi	0 to 3.15
[75]	HMA	AC 20	Addition of slag cement paste	0, 10, 20, 30, 40 wt	C	4.0 to 12
[76]	HMA	AH 70	Chemical: silane-based water repellent agents	0, 50, 62 y 94 wt	C	4.75 to 25
					C-Fi	0.075 to 25
[41]	HMA	AC 50-70	Curing the mixture for 4 h at 170 °C	0, 1.25, 2.5, 5, 7.5 wt	C	8 to 16
				7.5 wt		4 to 8
[77]	HMA	AC 60-70	Chemical: Addition of organic silicon resin	0, 30, 60, 100 wt	C-Fi-Filler	0.075 to 31.5
[78]	HMA	AC 50-70	Chemical: Addition of Asphalt Emulsion	0, 2.5, 5, 10, 15 wt	C	4 to 16
[42]	HMA	NS	Chemical-mechanical	0, 13.2 wt	C	4.75 to 19
			thermal mechanical			
[79]	DBM	VG AC 30	Addition of polyethylene waste	0, 54 wt	C	4.75 to 26.5
[80]	HMA	VG AC 30	Addition of asphalt emulsion and polyethylene waste	0, 54 wt	C	4.75 to 26.5
[81]	HMA	AC 60-70	Mechanic: Wear on the Angels' Machine with 50, 100 and 200 turns	0, 21 wt	C	9.5 to 19
[82]	HMA	AC 50-70	Subjection for 4 h at 170 °C	0, 5, 10, 20, 30 wt	C-Fi	0.075 to 16
[83]	HMA	AC 60-70	Chemical: immersion in hydrochloric acid (HCl) and impregnation with calcium metasilicate	0, 6.25, 12.50 wt	C	4.75 to 19
[84]	HMA	AC 330	Asphalt emulsion for 90 min at 155 °C	0, 20, 40, 60 wt	C	4.75 to 19
[85]	DBM	VG AC 30	Addition of asphalt emulsion and polyethylene waste	0, 54 wt	C	4.75 to 26.5
[86]	HMA	AC 320	Mechanical in Los Angeles machine and thermal by heating to 180 °C and cooling	0, 100 wt	C-Fi-Filler	0 to 14
[87]	HMA	VG AC 30	Mechanic on the Los Angeles machine for 20 min with 8 spheres and the addition of lime	0, 3.5, 7, 11, 14, 18 wt	C	4.75 to 19
[88]	HMA	AC 60-70	Chemical: Magnesium sulfate solution	0, 21 wt	C	9.5 to 19
[89]	HMA	AC 40-50	Chemical: Acetic acid solution and carbon fibers	0, 8, 16, 24, 32, 40 wt	C	4.75 to 19
[90]	HMA	AC 40-50	Chemical: Acetic acid solution and steel fibers	0, 10, 20, 30 wt	C	4.75 to 19
[91]	HMA	AC 40-50	Chemical: Addition of a diluted solution of HCl and recycled polypropylene polymer	0, 10.4, 20.8, 31.6 wt	C	4.75 to 19
[92]	HMA	AC 50-70	Chemical: Addition of a polymeric additive to reduce absorption.	0, 10, 11.5, 12.5 wt	C	4.75 to 25

Note: Coarse (C); Fine (Fi).

The manuscripts reviewed and presented in Table 2 are described below in chronological order.

Wong et al. [74] produced HMA by replacing mineral filler (6 wt%) and the fine–filler fraction of NA with RCA (45% relative to the total aggregates, particle size between 3.15 mm and 19 mm). Additionally, an HMA was produced using thermally treated RCA (fine–filler fraction) to induce the detachment of the adhered mortar. The thermal treatment consisted of heating the RCA at 450 °C for one hour, followed by a temperature increase to 950 °C for two hours. The Marshall test was used for mix design, and RM test and dynamic creep test were performed to evaluate stiffness and rutting resistance using AC 60-70. Marshall test results indicated that all HMA with RCA met the criteria of the Singapore Land Transport Authority (LTA) for pavement construction. The OAC, RM, and rutting resistance of HMA with 6% RCA remained the same as the control mixture (100% NA). However, mixtures with 45% RCA exhibited increased values in these parameters, with higher results observed for the thermally treated RCA mix. In general, the results indicate good performance of RCA in HMA, which may be attributed to its mineralogical composition. Chemical characterization tests on RCA revealed the presence of quartz (SiO_2), calcite ($CaCO_3$), and portlandite ($Ca(OH)_2$), which can exhibit pozzolanic behavior and increase mixture stiffness.

Lee et al. [75] applied a surface treatment to RCA by incorporating slag cement paste to produce HMA. For this purpose, coating layers of 0.25, 0.45, and 0.65 mm thickness of slag cement paste were applied onto the surface of coarse RCA particles, with 0.25 mm identified as the optimum paste thickness for HMA. Replacements of 0%, 25%, 50%, 75%, and 100 wt% of the coarse fraction of NA (40% of total aggregates, particle size between 4.0 mm and 12 mm) were made using RCA treated with a 0.25 mm slag cement paste coating. Marshall, ITS, TSR, and rutting resistance tests were conducted to evaluate the mechanical behavior of the mixtures. The results showed that OAC and Av increased with the amount of treated RCA, while S decreased. Overall, the mixtures complied with the specifications for asphalt mix design established by the Ministry of Transportation and Communications of Taiwan. ITS improved in the mixtures with treated RCA; however, TSR and rutting resistance values decreased compared to the control mixture (0% RCA). Generally, the results indicate that indirect tensile performance improved with treated RCA, but compressive performance worsened relative to the control. The authors did not include a mix with untreated RCA, which limits the analysis.

Zhu et al. [76] studied CDW originating from buildings damaged by the Wenchuan earthquake in China for the production of asphalt mixtures using AH 70 binder. To reduce water absorption and improve the strength of CDW, silane-based water repellent agents were used to pretreat the particles. CDW aggregates were immersed in liquid silicone resin for one hour and then cured in an oven at 60 °C for 24 h to solidify the silicone resin. Asphalt mixtures were produced by replacing the fine–coarse fractions (particle size between 0.075 mm and 25 mm), total coarse fraction (particle size between 4.75 mm and 25 mm), and partial coarse fraction (particle size between 4.75 mm and 25 mm) of NA with RCA. Additionally, one mixture was prepared with partial substitution of the coarse fraction using treated CDW. The fine–coarse, total coarse, and partial coarse fractions represented 94%, 62%, and 50% of the total aggregate mass, respectively. Marshall test, ITS, TSR, rutting resistance, and flexural strength tests were performed. Results showed that OAC, Av, and rutting resistance increased with CDW content, while S, ITS, TSR, and flexural strength decreased compared to the control mixture (0% CDW). However, the treatment significantly improved the physical properties, moisture susceptibility, rutting resistance, and flexural strength of the asphalt mixtures when compared to those containing untreated CDW.

Pasandín and Pérez [41] studied the replacement of 0% (control), 5%, 10%, 20%, and 30 wt% of the NA fraction with particle sizes between 8.0 mm and 16 mm by RCA for the production of an HMA using AC 50–70. The replaced fraction represented 20 wt% of the total aggregate content. Additionally, one mixture was prepared by replacing 30 wt% of the NA fraction with particle sizes between 4.0 mm and 8.0 mm (representing 25 wt% of the total aggregates). To improve adhesion, a loose asphalt mixture (uncompacted) was subjected to 170 °C in an oven for 4 h in order to facilitate filling of the surface voids of the

RCA. Marshall, ITS, TSR, RM, permanent deformation, and strain-controlled fatigue tests were conducted. The results indicated a slight reduction in OAC in mixtures with 5% and 10% RCA, while it increased for mixtures with 20% and 30% RCA. Overall, the HMA with 5% RCA showed higher S, ITS, TSR, and rutting resistance compared to the control mixture. Regarding RM and fatigue, performance was similar to that of the control HMA. Although the mixtures with 10%, 20%, and 30% RCA exhibited higher ITS and TSR, reductions were observed in S, rutting resistance, and fatigue performance compared to the control. The heat treatment at 170 °C for 4 h improved adhesion, but the authors did not compare these results with mixtures made without such treatment. Moreover, the RCA contents used were low (maximum 7.5% of the total aggregate mass), limiting the full utilization of RCA. The authors did not prepare mixtures with untreated RCA, making it difficult to assess the treatment's influence on mixture performance.

Hou et al. [77] evaluated the mechanical behavior of an asphalt base mixture using RCA aggregate treated with 0%, 2%, and 4 wt% of organic silicon resin, metatitanic resin acceptor, and silane resin acceptor as surface activators. These materials were sprayed onto the RCA surface, followed by mechanical agitation for 5 min and then an air-drying rest period of 3 to 4 h. Physical characterization tests indicated that organic silicon resin was the most effective in reducing both crushed value and water absorption. Based on these results, asphalt mixtures were produced by replacing 0%, 30%, 60%, and 100% of the NA (particle size between 0.0 mm and 31.5 mm) with RCA treated with organic silicon resin. AC 60-70 was used as the binder. To evaluate mechanical performance, Marshall, RTI, ITS, TSR, and low-temperature bending resistance tests (–10 °C) were conducted. The results showed that both OAC and Av increased with the treated RCA content. However, S, ITS, and TSR decreased slightly. Additionally, improved resistance to low-temperature deformation was observed in mixtures with treated RCA compared to the control mixture (0% RCA). The authors did not assess the mechanical behavior of mixtures with untreated RCA, making it impossible to determine the specific influence of the RCA surface treatment on the mechanical performance of the mixtures.

Pasandín and Pérez [78] investigated the replacement of 5%, 10%, 20%, and 30% of the coarse fraction of NA with RCA particles for the production of an HMA using AC 50–70. The coarse fraction (particle size between 4 mm and 16 mm) accounted for 50% of the total aggregate content in the mixture. To address the issue of high surface porosity in RCA, the authors coated the particles with 5% asphalt emulsion. Tests were conducted to evaluate volumetric composition and mechanical performance through ITS, TSR, RM, rutting resistance, and fatigue tests, using asphalt contents of 3.5%, 4.0%, and 4.5%. The results for Av, ITS, and TSR did not exhibit a clear trend with RCA content or asphalt content, as no results were provided for a control mixture (0% RCA). However, the mixtures generally complied with Spanish construction specifications for use in asphalt base layers. The asphalt emulsion treatment improved the homogeneity of RCA, as evidenced by lower variations in RM compared to untreated RCA. Nevertheless, no clear trend was observed in RM with respect to RCA or asphalt content compared to the untreated RCA mixtures. Overall, RCA-treated mixtures exhibited lower rutting resistance than untreated mixtures. On the other hand, fatigue curves for treated RCA mixtures showed behavior similar to the control mixture. These findings suggest that the RCA treatment with asphalt emulsion was not effective in improving the mechanical performance of the HMA.

Giri et al. [79] produced asphalt mixtures by replacing the coarse fraction of NA with RCA (particle size between 4.75 mm and 26.5 mm, accounting for 54 wt% of the total aggregates). Additionally, 2.0% and 3.0 wt% of polyethylene waste from milk containers were incorporated onto the RCA surface (dry process) to enhance mixture adhesion. Two different types of fillers were also used: cement and stone dust. The mixtures were prepared using VG-30 asphalt. Marshall, ITS, TSR, dynamic modulus, and rutting resistance tests were performed to evaluate the mechanical performance. Marshall test results showed that all mixtures met the requirements of Indian road construction specifications. Mixtures containing RCA exhibited reduced ITS, TSR, dynamic modulus, and rutting resistance compared to mixtures with NA. However, the use of cement as filler and the addition of polyethylene waste mitigated these reductions. In other words, treating RCA with polyethylene waste improved performance compared to untreated RCA mixtures. Subsequently, the authors conducted a follow-up study [80] using an 8% compound (comprising 40% asphalt emulsion and 60% water) to pretreat RCA to produce a dense bituminous macadam (DBM) mixture. As in the previous study, VG-30 asphalt was used, and 54 wt% of NA was replaced with pretreated RCA (particle size between 4.75 mm and 26.5 mm), along with polyethylene waste from milk containers to improve adhesion. Marshall, ITS, TSR, RM, and rutting resistance tests were conducted. All mixtures complied with Marshall parameters according to Indian construction specifications. RCA mixtures showed an increase in OAC compared to the control mix; however, OAC was reduced when the RCA was treated, and polyethylene waste was added. The authors reported a slight increase in Marshall stability and RM in mixtures containing RCA (both treated and untreated) compared to the control. An improvement in moisture damage resistance was also observed. Nonetheless, ITS at 20 °C and rutting resistance were reduced. Overall, the treatment and addition of polyethylene waste improved the mechanical performance of RCA-containing mixtures.

Al-Bayati et al. [42] evaluated two surface treatments for RCA aimed at reducing porosity and enabling their use in asphalt mixtures: (i) chemical-mechanical and (ii) thermal-mechanical treatments. For this purpose, coarse RCA particles (particle size between 4.75 mm and 19 mm) were used, representing approximately 44% of the total aggregate content in the mixture. In the chemical-mechanical treatment, the RCA was immersed in an acetic acid solution for 24 h at room temperature. In the thermal-mechanical treatment, particles were washed with distilled water and then subjected to 300 °C in a conventional oven for one hour. In both cases, a mechanical pretreatment was conducted using a micro-Deval device with steel spheres under dry conditions for 15 min. Afterward, the material was washed and oven-dried at 105 ± 5 °C for 24 h and subsequently sieved through a No. 4 sieve. Asphalt mixtures were produced by replacing 0%, 15%, 30%, and 60% of NA with untreated RCA, employing the Superpave design methodology for traffic levels between 10 and 30 million ESALs. To assess the influence of RCA treatment, only mixtures with 30% RCA were evaluated. The results showed that the mixture incorporating chemically and mechanically treated RCA exhibited a similar OAC compared to the control mix (0% RCA), but a reduction in comparison to the mixture with untreated RCA. Conversely, OAC increased in the mix with thermally and mechanically treated RCA, both in reference to the control and to the untreated RCA mix. In all mixtures, Av values remained similar. Overall, mixtures containing RCA (treated and untreated) complied with Canadian asphalt mixture specifications. However, the production costs for mixtures with 30% and 60% RCA were higher than the control mix, mainly due to the treatment processes. In contrast, the mixture with 15% untreated RCA showed a lower manufacturing cost compared to the control.

Pasandín and Pérez [82] produced an HMA with 0%, 5%, 10%, 20%, and 30 wt% replacement of NA (particle size between 0.075 mm and 16 mm) by RCA using AC 50–70. Prior to compaction, the loose mixtures were subjected to 170 °C for 4 h to facilitate filling of the RCA surface voids. Marshall, ITS, TSR, and rutting resistance tests were performed. Results indicated that thermal treatment of the HMA increased the OAC, Av, S, ITS, and TSR, as the absorbed asphalt reduced porosity, resulting in better coating of particles and enhanced resistance to moisture-induced damage. The best performance was observed in mixtures containing 5% and 10% RCA. Regarding the permanent deformation test, the influence of RCA was unclear, as the authors did not evaluate the control mixture (0% RCA).

Bastidas et al. [81] performed mechanical treatments on the coarse RCA fractions by subjecting them to 50, 100, and 200 revolutions in the Los Angeles abrasion machine to detach adhered mortar and reduce absorption. Subsequently, an HMA was produced partially replacing the coarse fraction (particle size between 9.5 mm and 19 mm, accounting for 21% of the total aggregates) of NA by RCA (untreated and treated with 50, 100, and 200 revolutions in the Los Angeles machine). Marshall, ITS, TSR, and Cantabro tests were performed. Results showed that mechanical treatment reduced absorption and improved RCA characteristics compared to NA. Additionally, mix designs revealed increased resistance under monotonic loading (higher S/F, ITS, and TSR values) and improved Cantabro wear resistance compared to control mixes with NA and untreated RCA. These findings indicate that Los Angeles machine treatment of RCA is effective; however, the experimental phase was limited, as no repeated load tests were conducted.

Kavussi et al. [83] chemically treated RCA particles (size between 4.75 mm and 19 mm) by immersing them in hydrochloric acid (HCl) for 24 h at room temperature to reduce the adhered mortar. Afterward, the particles were rinsed with distilled water to neutralize and remove the acid residues. Subsequently, the RCA was impregnated with calcium metasilicate (CM)—a fine solid material composed mainly of quartz (SiO_2) and calcite ($CaCO_3$)—for 24 h to fill surface voids. An HMA was then produced using AC 60-70, replacing 25% and 50 wt% of the NA coarse fraction (which represented 25% of the total aggregate mass) with RCA (both treated and untreated). To evaluate mechanical performance, ITS, TSR, and strain-controlled fatigue tests were conducted. No Marshall test results were reported. ITS and TSR values for both treated and untreated RCA mixtures slightly decreased compared to the control mix, a result attributed to low aggregate cohesion, high mortar permeability, and high abrasion values from the Los Angeles test for RCA. However, fatigue performance improved in the RCA mixtures—regardless of treatment—compared to the control. Overall, the chemical treatment slightly enhanced the mechanical behavior of the RCA mixtures compared to untreated RCA.

Giri et al. [85] continued their research by producing asphalt mixtures replacing 54 wt% of NA with treated RCA (coarse fraction sized between 4.75 mm and 26.5 mm). In this study, 8 wt% of a binder compound was applied to the RCA surface, consisting of 40 wt% medium-setting asphalt emulsion (MS) and 60 wt% water. After this treatment, polyethylene waste derived from milk containers was incorporated to enhance adhesion. Cement was used as a mineral filler, and VG-30 asphalt served as the binder. To evaluate performance, Marshall, ITS, TSR, RM, dynamic modulus, and rutting resistance tests were conducted. All mixtures met the Indian specifications for pavement construction. Compared to untreated RCA mixtures, treated RCA mixtures showed lower OAC, Av, and ITS, but higher S, TSR, RM, dynamic modulus, and rutting resistance. Overall, these findings are promising, as they suggest that treated RCA can reduce asphalt demand while improving compressive strength and stiffness. However, a decrease in indirect tensile strength under monotonic loading was observed, indicating a potential trade-off in tensile performance.

Jitsangiam et al. [86] applied both mechanical and thermal treatments to RCA for the production of HMA using AC 320 (viscosity-grade asphalt). The RCA consisted of crushed concrete containing rocks, bricks, and debris in low proportions. The mechanical treatment involved subjecting the RCA to 500 revolutions in the Los Angeles abrasion machine, followed by sieving, washing, and drying. The thermal treatment consisted of heating the RCA at 180 °C for 24 h and then rapidly cooling it with water, repeated three times. Physical characterization tests of the treated RCA were conducted. HMA was produced by replacing 0% and 100 wt% of the NA with treated RCA. Marshall, RM, dynamic modulus, ITS, and TSR tests were conducted to assess mechanical behavior. Physical characterization results indicated that absorption was reduced by 8% and 10% after mechanical and thermal treatments, respectively, compared to the control mixture with NA. In the HMA with treated RCA, the air void (Av) decreased by 0.2%, while OAC increased by the same percentage. Additionally, treated RCA increased stability (S) and RM, but dynamic modulus, ITS, and TSR values decreased. The absence of data from untreated RCA mixtures hinders an accurate evaluation of the treatment's effectiveness.

Kareem et al. [93] conducted a treatment to reduce the surface absorption of RCA by coating it with asphalt emulsion. The uncompact HMA mixture was then heated at 155 °C for 90 min to promote adhesion of the emulsion to the RCA, although this process may cause short-term aging of the asphalt binder. The RCA studied also included small proportions of RAP, brick debris, and other materials, complicating the analysis. HMA was produced by replacing 0%, 20%, 40%, and 60% of the NA coarse fraction (particle size between 4.75 mm and 19 mm), using AC 330 (viscosity-grade asphalt). Marshall, dynamic modulus, permanent deformation, and four-point bending fatigue tests were conducted. Results showed that all mixtures met Australian specifications. Treated RCA mixtures exhibited lower OAC compared to untreated RCA, while maintaining similar Av. Furthermore, dynamic modulus, rutting resistance, and fatigue performance improved in the treated RCA mixtures compared to the control mix. Mixtures containing 40% and 60% treated RCA showed the highest fatigue resistance.

Singh et al. [87] crushed concrete sample cylinders using the Los Angeles abrasion machine for 20 min with 8 steel spheres in order to reduce the amount of adhered mortar from the RCA. Subsequently, a HMA was produced using VG 30 asphalt cement, replacing 0%, 10%, 20%, 30%, 40%, and 50 wt% of the coarse fraction of NA (sized between 4.75 mm and 19 mm) with RCA. The coarse fraction represents approximately 35 wt% of the total aggregate mass. In addition, the influence of hydrated lime on the surface of RCA was evaluated using contents of 0% and 2% (based on the total mass of aggregates in the HMA). Marshall stability, ITS, and TSR tests were conducted to assess the performance of the mixtures. The mix designs complied with the specifications for HMA construction in India. The results indicate that RCA increases the OAC compared to the control mix (0% RCA). Mixtures containing RCA without hydrated lime exhibited lower stability (S), S/F, ITS, and TSR values compared to the control mix. However, the addition of hydrated lime improved the mechanical performance of the HMAs. HMAs containing 40%, 20%, 10%, and 30% RCA with 2% hydrated lime exhibited similar values of S, S/F, ITS, and TSR to the control HMA, respectively. The economic and environmental evaluation showed that the cost of HMAs with RCA (with and without hydrated lime) was 0–3% higher than the control mix. Nevertheless, the carbon dioxide (CO_2) emissions of the mixtures containing RCA were reduced by 2–8%. Therefore, the authors concluded that the increase in economic cost is minor when considering both economic and environmental aspects.

Bastidas et al. [88] conducted chemical treatments on RCA surfaces using a magnesium sulfate solution with 1, 3, and 5 immersion cycles, according to the aggregate durability test specified by AASHTO T 104-99. Subsequently, asphalt mixtures were prepared by replacing the coarse fraction (sized between 9.5 mm and 19 mm) of NA with RCA (both untreated and chemically treated). The replaced fraction corresponded to 21 wt% of the total aggregate content. The mix designs were carried out using AC 60-70 asphalt binder. Monotonic load resistance tests (Marshall and ITS) and Cantabro abrasion resistance tests were performed. The results indicate that chemically treated RCA increases the resistance under monotonic loading (higher S and ITS under wet conditions), providing improved cohesion and a slight increase in adhesion compared to both the control mixtures (0% RCA) and the untreated RCA mixtures. Additionally, mixtures with chemically treated RCA exhibited lower Cantabro abrasion loss.

Abdulghafour et al. [91] analyzed the effect of using RCA obtained from CDW of a building in Iran to produce HMA using AC 40-50. To reduce surface absorption, the RCAs were immersed in a diluted HCl solution with a concentration of 0.1 moles for 24 h to remove the cement mortar. Subsequently, the treated RCA was left to dry and finally subjected to a sieving process to comply with the coarse fraction standards required for the wearing course (particle size between 19 mm and 4.75 mm). Mixtures were prepared using the Marshall test, replacing 0%, 20%, 40%, and 60 wt% of the NA coarse fraction with RCA (treated and untreated), considering a constant Av of 4%. The coarse fraction represents 52 wt% of the total aggregates. Additionally, the effect of incorporating 2%, 4%, and 6% of recycled polypropylene polymer using a dry process was analyzed through ITS and TSR tests. Logically, the results indicate that the OAC increases with RCA content; however, RCA treatment reduces it. The mixtures with RCA (treated and untreated) showed higher ITS, TSR, and compressive strength compared to the control mixture (0% RCA). Furthermore, the recycled polypropylene polymer increased the ITS and compressive strength in direct proportion to the added content. In terms of TSR, the highest increases occurred with 2% recycled polypropylene polymer. The authors explain that the rough surface of RCA improves the adhesion with asphalt, compressive strength, and tensile strength. Additionally, the use of recycled polypropylene polymer reinforces the bond between the aggregate and the asphalt, thus enhancing the structural integrity of the asphalt mixture.

Albayati et al. [89] treated RCA by immersion in an acetic acid solution for 24 h to be used in the production of HMA with AC 40-50. The 0%, 20%, 40%, 60%, 80%, and 100 wt% of the NA coarse fraction (particle size between 4.75 mm and 19 mm, representing 40 wt% of the total aggregates) was replaced by RCA. Marshall and rutting resistance tests were conducted. Additionally, carbon fibers (length of 20 mm) were added at percentages of 0.15%, 0.25%, and 0.35% relative to the total mixture weight. The results indicate that treated RCA increased Av, OAC, and S compared to the control mixture (0% RCA). Furthermore, both S and rutting resistance increased with the carbon fiber content. The best performance was achieved by the mixture with 100% replacement of the NA coarse fraction by treated RCA and 0.35% carbon fibers. In general, these results indicate that treated RCA generates a significant increase in compressive strength, as defined by S and rutting resistance. However, no tests were conducted to evaluate the tensile strength. Moreover, mixtures with untreated RCA were not produced, making it impossible to assess the effectiveness of the treatment.

Hussein et al. [90] immersed RCA in a hydrochloric acid solution for 24 h to be used in the production of HMA with AC 40-50. The 0%, 25%, 50%, and 75 wt% of the coarse fraction of the mixture (particles between 19 mm and 4.75 mm, which represent 40% of the total aggregates) of NA were replaced by treated RCA. Additionally, 0%, 0.3%, 0.6%, and 0.9% of steel fibers (relative to the total mass of the mixture) were incorporated to reinforce the mixture. To evaluate the mechanical behavior of the mixtures with RCA, Marshall and rutting resistance tests were conducted. Results indicate that OAC increased in the mixtures with treated RCA (considering Av = 4%). Likewise, the addition of fibers led to higher S values, with the highest values reported for the mixture with 75 wt% RCA and 0.9% steel fibers. Mixtures with treated RCA and steel fibers exhibited higher rutting resistance compared to the control mixture (with NA). The authors did not produce mixtures with untreated RCA, making it difficult to verify the effectiveness of the RCA treatment.

Moreno-Anselmi [92] investigated CDW in asphalt mixtures using a surface treatment with a polymeric additive primarily applied to reduce absorption. Mixtures were produced according to two technical specifications, including one from the "Departamento Nacional de Infraestrutura de Transportes (National Department of Transport Infrastructure)" (DNIT) in Brazil and another from the "Instituto Nacional de Vías (National Institute of Roads)" (INVIAS) in Colombia, using AC 50-70. These correspond to HMA-19 and HMA-25, respectively. The NA size fractions from 25 to 19 mm, 19 to 12.5 mm, and 12.5 to 9.5 mm were replaced by treated CDW. In HMA-19, the 19–12.5 mm and 12.5–9.5 mm fractions represent 10%. In HMA-25, the 25–19 mm, 19–12.5 mm, and 12.5–9.5 mm fractions account for 12.5%, 11.5%, and 10%, respectively. Marshall test, ITS, TSR, RM, static creep, and fatigue tests were performed. Additionally, a detailed morphological analysis of the CDW particles was conducted using 3D scanning and scanning electron microscopy (SEM) to correlate the shape and texture of the treated CDW with the mixture performance. The results indicate that the OAC decreased in mixtures with treated CDW compared to mixtures with untreated RCA. Moreover, higher values of S, ITS, TSR, RM, rutting resistance, and fatigue resistance were obtained in mixtures with treated CDW, compared to untreated CDW, indicating greater internal cohesion and mechanical performance. Similarly, values comparable to the control mixture with 100% NA were also achieved.

A summary of the review described in Section 4 is shown in Table 3.

Table 3. Studies of asphalt mixtures with treated RCA.

Author	RCA (%)	Compaction	Respect to Control (0% RCA)								Respect to Asphalt Mix with RCA (Without Treatment)							
			OAC	Av	S	ITS	TSR	Stiffness	Resistance to		OAC	Av	S	ITS	TSR	Stiffness	Resistance to	
									Rutting	Fatigue							Rutting	Fatigue
[74]	0, 6, 45 wt	Marshall	Si	Si	I	----	----	I	----	----	----	----	----	----	----	----	----	----
			I	I	I	----	----	I	----	----	I	Si	D	----	----	D	----	----
[75]	0, 10, 20, 30, 40 wt	Marshall	I	Si	D	I	D	----	I	----	----	----	----	----	----	----	----	----
[76]	0, 50, 62 y 94 wt	Marshall	I	I	D	D	D	D	I	----	----	----	----	----	----	----	----	----
			I	I	D	D	D	D	I	----	D	Si	I	I	D	D		
[41]	0, 1.25, 2.5, 5, 7.5 wt	Marshall	I	I	D	D	I	I	D	D	----	----	----	----	----	----	----	----
	7.5 wt	Marshall	I	I	I	D	I	D	D	D	----	----	----	----	----	----	----	----
[77]	0, 30, 60, 100 wt	Marshall	I	I	D	D	D	----	----	----	----	----	----	----	----	----	----	----
[78]	0, 2.5, 5, 10, 15 wt	Marshall	----	----	----	----	----	----	----	----	----	----	----	*	*	*	D	Si
[42]	0, 13.2 wt	Superpave	Si	Si	----	----	----	----	----	----	D	Si	----	----	----	----	----	----
			I	Si	----	----	----	----	----	----	I	Si	----	----	----	----	----	----
[79]	0, 54 wt	Marshall	I	I	I	D	D	D	D	----	D	D	I	I	I	I	I	----
[80]	0, 54 wt	Marshall	D	I	I	D	I	D	D	----	D	Si	I	I	I	I	I	----
[81]	0, 21 wt	Marshall	I	I	I	I	I	----	----	----	Si	D	I	I	I	----	----	----
[82]	0, 5, 10, 20, 30 wt	Marshall	----	----	----	----	----	----	----	----	I	I	I	I	I	----	----	----
[83]	0, 6.25, 12.50 wt	Marshall	----	----	----	D	D	----	----	I	----	----	----	I	I	----	----	I
[84]	0, 20, 40, 60 wt	Marshall	D	Si	I	----	----	I	I	I								
[85]	0, 54 wt	Marshall	D	Si	I	D	I	I	I	----	D	D	I	D	I	I	I	----
[86]	0, 100 wt	Marshall	I	D	I	D	D	I	----	----	----	----	----	----	----	----	----	----
[87]	0, 3.5, 7, 11, 14, 18 wt	Marshall	I	Si	I	I	I	----	----	----	----	----	I	I	I	----	----	----
[88]	0, 21 wt	Marshall	I	I	I	I	I	----	----	----	Si	D	I	D	I	----	----	----
[89]	0, 8, 16, 24, 32, 40 wt	Marshall	I	I	I	----	----	----	I	----	----	----	----	----	----	----	----	----
[90]	0, 10, 20, 30 wt	Marshall	I	I	I	----	----	----	I	----	----	----	----	----	----	----	----	----
[91]	0, 10.4, 20.8, 31.6 wt	Marshall	I	Si	I	I	I	----	----	----	D	Si	I	I	I	----	----	----
[92]	0, 10, 11.5, 12.5 wt	Marshall	I	I	S	D	D	D	S	I	D	D	I	I	S	I	I	I

Note: No Specific (NS); Increase (I); Decrease (D); Similarly (Si); * Contribution is not clear.

5. Discussion

Based on the information from studies on RCA in asphalt mixtures presented in Table 1 and its corresponding chronological description, the following observations can be made: (i) The coarse aggregate fraction (particle size between 4.75 mm and 19 mm) is generally replaced either partially or fully, typically representing between 10% and 50% of the total mixture mass. (ii) Few studies have assessed the effect of substituting the fine fraction of NA (particle size between 0.075 mm and 4.75 mm) with RCA. Results indicate a significant increase in the OAC, as the fine RCA particles exhibit higher absorption and lower specific gravity compared to those in the coarse fraction [69,71,81]. Additionally, fine RCA is primarily composed of mortar, which tends to be fragile and brittle, and exhibits higher absorption compared to NA. Tahmoorian et al. [94] reported that RCA particles with water absorption values exceeding 4% tend to exhibit poor performance in asphalt mixtures. (iii) Most studies perform aggregate replacement on a mass basis rather than by volume. However, since RCA has a lower specific gravity than NA, mass-based replacement leads to a higher number of particles in the mix, which may alter the volumetric composition (resulting in increased air voids and reduced asphalt coating efficiency on the RCA surfaces (See Figure 3). Therefore, volume-based replacement of NA with RCA is recommended [71]. (iv) In general, asphalt mixtures containing RCA exhibit a higher OAC and increased air voids, which may contribute to reduced stiffness and rutting resistance.

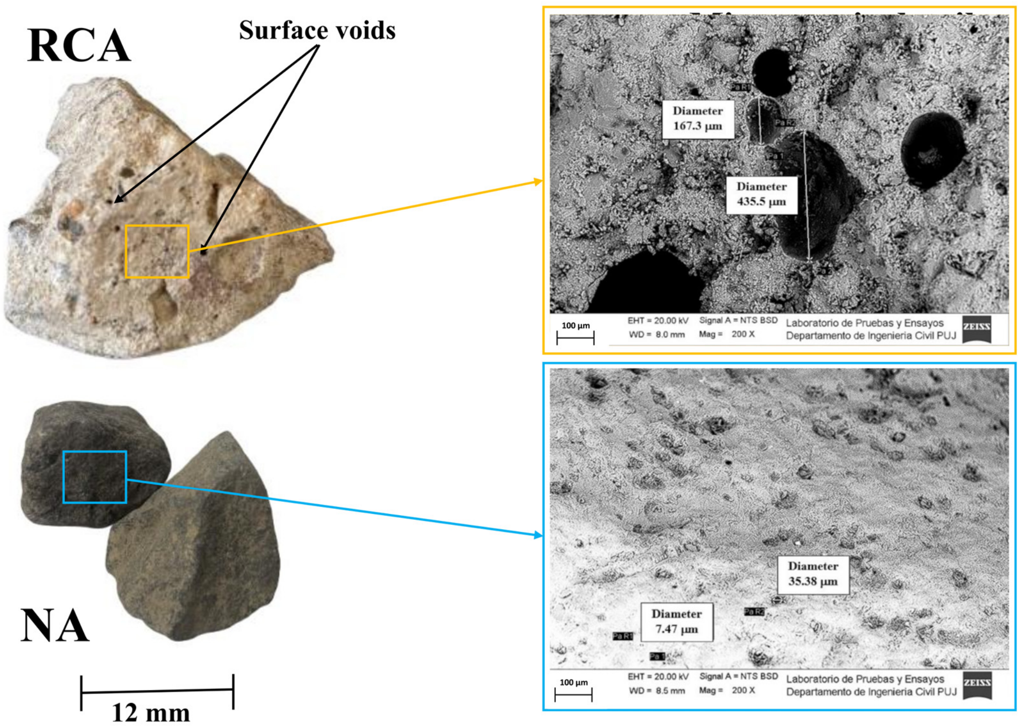

Figure 3. Microscopic view of surface absorption in RCA and NA.

(v) The mechanical behavior of RCA mixtures is highly variable and depends on the physicochemical properties of the material (e.g., chemical alterations on the surface may weaken the aggregate–binder bond), the type of residual cement, the source of NA, and the origin of the RCA. Furthermore, the presence of adhered mortar can influence mechanical performance, as it tends to detach easily and has high absorption capacity (See Figure 4). For instance, it has been observed that RCA derived from older demolished buildings performed worse compared to RCA obtained from construction waste [68]. The heterogeneity of RCA—due to the presence of adhered mortar fragments, varied sources, and impurities such as brick, ceramic, or even wood—leads to highly variable physical and mechanical properties, unlike natural aggregates, which exhibit greater consistency. (vi) Some studies have successfully designed RCA asphalt mixtures with air void contents comparable to those of control mixtures [1,39,50,51]. However, the mechanical behavior of mixtures containing RCA is highly variable, as it largely depends on the physicochemical characteristics of both RCA and NA. (vii) The use of high-consistency binders (e.g., AC 40–50) or modified asphalts tends to enhance the mechanical performance of RCA mixtures, primarily by increasing stiffness and rutting resistance. (viii) Regarding moisture susceptibility, most studies report that mixtures incorporating RCA exhibit a reduction in the TSR compared to control mixtures. Therefore, surface treatments on RCA particles—such as mechanical or chemical modification, or the addition of supplementary materials—are recommended to improve the aggregate–binder adhesion [83,84,95–97]. Most studies report that RCA is a promising material for use in low-traffic volume roads.

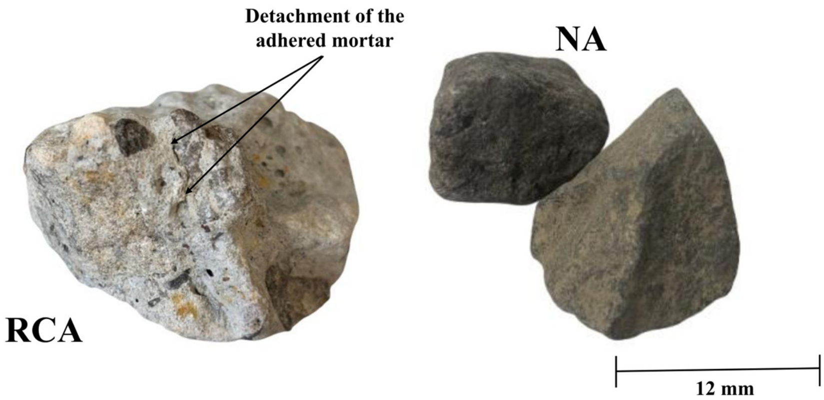

Figure 4. Adhered mortar on an RCA particle.

As shown in Table 1, untreated RCA led to changes in the evaluated parameters. In some cases, increases (I) were observed, in others the properties remained similar (S), and in some cases, decreases (D) were reported. In summary, considering all the reviewed studies, Figure 5 presents the percentage trends of the evaluated parameters relative to the control mixture. According to these findings, mixtures containing RCA tend to exhibit higher optimum asphalt content (OAC) and air voids (Avs). Approximately 70% of the reviewed studies reported improvements in tests related to monotonic load resistance (Marshall/ITS), rutting resistance, and fatigue performance. However, around 65% of the studies showed a reduction in tensile strength ratio (TSR) and stiffness values.

On the other hand, based on the conducted review, the following research gaps have been identified: (i) There are no widely accepted standards for characterizing and classifying RCA for use in asphalt mixtures, complicating quality control and comparison across studies. (ii) The physicochemical interaction between mortar and asphalt has been insufficiently studied. Techniques such as FTIR, DSC, or spectroscopy could be employed to analyze molecular-level interactions and their effects on adhesion and aging. (iii) Few studies evaluate the long-term performance of RCA mixtures in terms of durability and resistance (e.g., aging). Additionally, full-scale testing to validate laboratory experiments is lacking. (iv) The compatibility of RCA with modified binders remains unclear. (v) It is not well understood how the source of the original concrete significantly influences RCA properties. Few studies have developed classification systems based on source origin (e.g., industrial vs. residential demolition, concrete age, etc.). (vi) Few numerical or computational models have been developed to simulate the performance of RCA mixtures. (vii) Most studies focus on mechanical property measurements rather than life cycle assessment

(LCA) or economic evaluations. (viii) Few studies compare RCA with other wastes such as CDW, blast furnace slag, steel slag, RAP, etc.

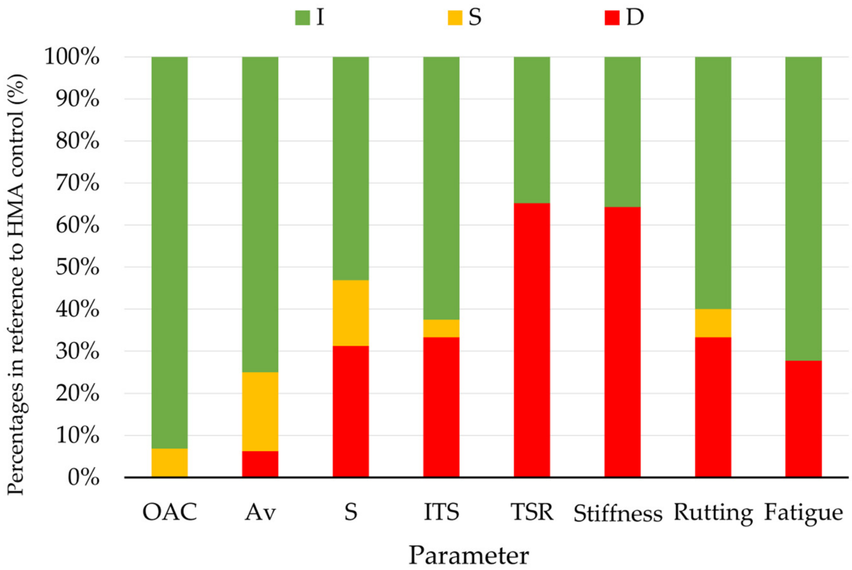

Figure 5. Percentages of I, S, and D in parameters reported in studies of mixtures with untreated RCA.

Based on the information reported in Tables 2 and 3 regarding surface treatments of RCA, the following observations can be made: (i) Most studies performed replacement of the coarse aggregate fraction or total NA with RCA for the production of asphalt mixtures. (ii) All presented studies on treated RCA report the use of original (unmodified) asphalt binders. (iii) In general, most studies on untreated RCA asphalt mixtures indicate an increase in OAC and air voids. However, surface treatments result in a reduction of these parameters compared to untreated RCA mixtures. This highlights the effectiveness of surface treatments on RCA, particularly with the addition of asphalt emulsion and plastic waste, which can seal surface voids [80,85,94]. Additionally, the use of asphalt emulsion increases Marshall stability, stiffness, and rutting resistance—that is, resistance to compressive loads mainly at elevated temperatures (around 60 °C). (iv) Most surface treatments improved indirect tensile strength compared to untreated RCA mixtures. This improvement is attributed to increased adhesion between RCA particles and asphalt, likely due to the removal of the adhered mortar coating [76,79–83,87,91]. (v) Surface treatments of RCA using silane-based water repellent agents have been applied to particles ranging in size from 0.0075 mm to 25 mm [76] but was not effective in improving resistance to moisture-induced damage, as evidenced by the reduction in the TSR parameter. (vi) Only Hou et al. [77] evaluated low-temperature cracking in RCA mixtures, reporting improved performance when incorporating organic silicon resin as an additive.

In summary, considering all the reviewed studies on mixtures with treated RCA, Figure 6 presents the variations (I, D, or S) in the evaluated parameters relative to untreated RCA. In general, surface treatments tend to reduce or maintain similar values of optimum asphalt content (OAC) and air voids (Avs). Furthermore, the reviewed studies show greater improvements in the evaluated parameters compared to mixtures containing untreated RCA.

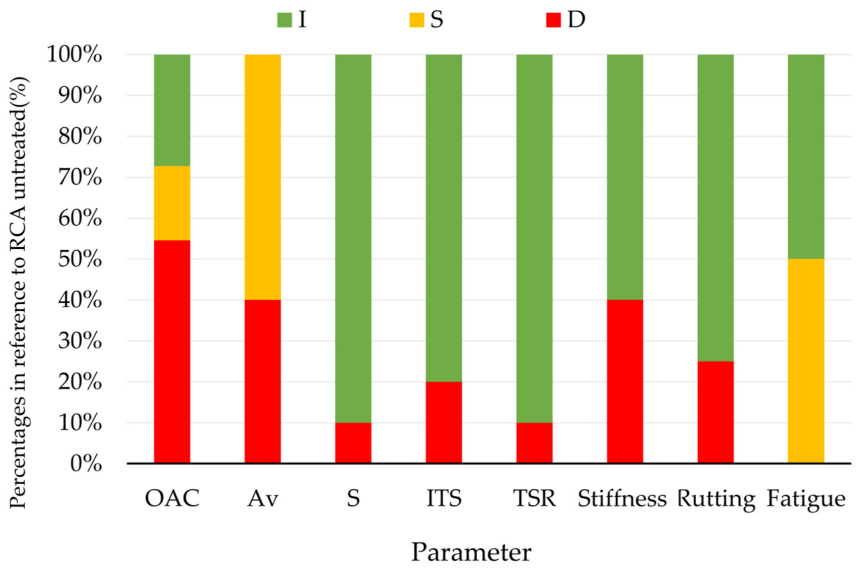

Figure 6. Percentages of I, S, and D in parameters reported in studies of mixtures with treated RCA.

Table 4 summarizes the main advantages and disadvantages associated with the use of RCA in asphalt mixtures, as identified in this study.

Table 4. Summary of advantages and disadvantages of using RCA in asphalt mixtures.

Advantages	Disadvantages
• Utilization of construction and demolition waste as alternative materials. • Reduction in the extraction of natural aggregates. • At low replacement levels (below 30%), the mechanical performance may be similar to or better than that of the control mixture. • Due to the crushing process, RCA can provide more angular and cubical particles, enhancing internal aggregate interlock, stiffness, and strength. • Higher surface texture of RCA, which can improve pavement surface properties. • Surface treatments applied to RCA can reduce its absorption and enhance the performance of the mixtures compared to untreated RCA.	Higher asphalt content requirements, which may increase the production cost of the mixture. At high replacement levels (above 50%) or when replacing the fine fraction, the mechanical performance of the mixture may deteriorate compared to natural aggregates. High heterogeneity of RCA particles, which may negatively affect mixture performance. The use of fine RCA materials can lead to excessive asphalt consumption and reduce particle cohesion and adhesion. The low specific gravity of RCA may result in a higher number of particles in the mixture when replacements are made by mass, suggesting that volumetric mix designs should be considered.

On the other hand, the following research gaps have been identified: (i) Many studies do not compare the performance of untreated and treated RCA mixtures, which complicates analysis. In most cases, the reference (control) mixture consists of 100% NA. (ii) Few fatigue studies have been conducted on treated RCA asphalt mixtures (see Table 3). (iii) There is no standardized methodology for applying treatments, including agent type, dosage, curing time, temperature, etc. (iv) Most studies assess initial properties but do not evaluate how treated RCA performs under aging, moisture exposure, freeze–thaw cycles, and other environmental conditions. (v) Limited knowledge exists regarding the interaction between treatments and different binder types (conventional, modified, bio-asphalt). (vi) Some treatments (e.g., epoxy or thermal coatings) may entail high energy consumption or have negative environmental impacts. Therefore, life cycle assessment (LCA) and life cycle cost analysis (LCCA) should be incorporated to evaluate their practical feasibility. (vii) Many treatments are effective at the laboratory scale but have not been tested for applicability at plant or field scale.

In summary, although RCA treatments offer clear improvements, there is still a lack of systematic, long-term, and industry-transferable knowledge. This gap presents a significant opportunity for comprehensive research integrating laboratory experiments, modeling, environmental analysis, and field validation.

6. Conclusions

Based on the literature review, the following conclusions can be drawn:

- RCA has potential for use in the production of asphalt mixtures. In general, the studies meet specifications for pavement layer construction, primarily for low-traffic volume roads.
- Most studies replace the coarse fraction of NA in the mixture with RCA (both treated and untreated), likely due to the ease of obtaining particle sizes between 4.75 mm and 19 mm from crushing plants. However, there is no established specification for the particle size distribution of RCA used in mixture production.
- Few studies have focused on the fine fraction of RCA, due to the increased surface area and higher asphalt absorption of these particles. Moreover, producing particle sizes between 0.075 mm and 4.75 mm in crushing plants demands higher energy consumption and production costs at concrete recycling facilities.
- There is no consensus on the mechanical behavior of asphalt mixtures containing RCA. Some studies report improved mechanical performance compared to NA, while others show the opposite. Approximately 70% of the studies involving RCA reported an increase in monotonic load resistance, rutting resistance, and fatigue performance. Approximately 65% of the studies reported a reduction in stiffness and TSR parameter. This inconsistency is attributed to the heterogeneity of RCA, the source and origin of CDW, and their physicochemical properties.
- Surface treatments applied to RCA cause partial removal or wear of the adhered mortar coating, which reduces surface voids and lowers the OAC of the mixtures compared to untreated RCA. Approximately 70% of the reviewed studies reported either a reduction or similar behavior. Additionally, these treatments tend to enhance physicochemical interactions between particles, improving adhesion with the asphalt binder.
- In general, mixtures with RCA require adjustments in volumetric design and binder dosage to optimize mechanical properties.
- The inherent heterogeneity and variability of RCA—due to factors such as original concrete type, particle size, and amount of adhered mortar—limit its standardization. There is currently no clear or universal criterion to determine which RCA materials are suitable for asphalt mixtures, hindering regulatory approval and industrial acceptance.
- The use of RCA can reduce the consumption of natural aggregates and lower emissions associated with transporting virgin materials. However, some pretreatment or conditioning processes may increase the carbon footprint if not properly optimized.
- Few life cycle assessment (LCA) studies have comprehensively considered the actual impacts of treatments, transportation, and long-term performance.
- The application scale (laboratory versus industrial), costs, and compatibility with real-world asphalt mixtures remain underdeveloped topics. There is a significant lack of comparative studies between treatments and field validations under actual traffic and climatic conditions.

- The influence of adhered mortar surface characteristics (e.g., pH, porosity, chemical reactivity) on adhesion, aging, and long-term asphalt performance remains poorly understood. Advanced characterization techniques such as FTIR, XRD, SEM, and AFM are underutilized in this area.
- RCA possesses technical and environmental potential for incorporation into asphalt mixtures; however, its optimal use requires a systematic approach involving advanced characterization, effective treatments, standardization of methodologies, and comprehensive field validation.

Based on the identified research gaps, the following recommendations are proposed for future investigations: (i) Implement physical, mechanical, thermal, or other treatments on RCA to enable the full (100%) replacement of NA and maximize RCA utilization. (ii) Conduct mix design evaluations based on both volumetric and mass criteria to determine the most effective method for incorporating RCA into asphalt mixtures. (iii) Assess the effects of short- and long-term aging to evaluate the durability and performance of RCA containing mixtures over time. (iv) Investigate the physicochemical surface interactions between RCA and asphalt binder to better understand the microstructural properties influencing adhesion and performance. (v) Examine the incorporation of fine RCA fractions in asphalt mixtures, initially through testing in fine aggregate mixtures followed by evaluations in asphalt concrete. (vi) Explore the influence of supplementary materials such as high-viscosity modified asphalts, fibers, and additives to enhance the mechanical behavior of RCA mixtures. (vii) Evaluate the quality and performance of RCA after production, compaction, and placement in hot mix asphalt (HMA), considering the effects of both short- and long-term aging to detect any property changes. (viii) Investigate the effects of aging cycles, moisture exposure, freeze–thaw conditions, fatigue resistance, and permanent deformation in asphalt mixtures containing both treated and untreated RCA. (ix) Study the interactions between various surface treatments applied to RCA and different types of asphalt binders (conventional, modified, bio-asphalt). (x) Perform comprehensive life cycle assessments (LCAs) and life cycle cost analyses (LCCAs) of pavements containing RCA mixtures, both with and without treatments, to validate their feasibility and performance at plant and field scales.

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