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Review

Application of Aggregates from Construction and Demolition Wastes in Concrete: Review

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Abstract: In the current century, urbanization and the development of the construction industry have led to the generation of construction and demolition waste (CDW), imposing pressure on ecology and the environment. This has attracted the attention of industry personnel and researchers. This work discusses the current research on recycled coarse or fine aggregate, mainly focusing on the physical, mechanical and durability properties of sustainable concrete with recycled coarse or fine aggregate. Furthermore, it also summarizes CDW recycling and classification in major countries, the production processes of recycled aggregate, and the physical properties. This review will provide a reference for the application of concrete with recycled coarse or fine aggregate. Moreover, this review notes that replacing natural aggregates with both coarse and fine recycled aggregates awaits further experimental exploration.

Keywords: construction and demolition waste; green concrete; physical properties; mechanical properties; durability

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1. Introduction

Concrete has become a widely used building material, with the global concrete consumption estimated to be around 14 billion cubic meters in 2020, according to statistics from the Global Cement and Concrete Association (GCCA) [1]. Aggregates in concrete are an essential component, constituting approximately 75% of the total volume, and the ratio of fine to coarse aggregate usually is approximately 2:3. Currently, the greenhouse gas emissions from the extraction of natural aggregates account for about 1% of the total emissions from concrete production [2]. Further, the prevalent use of blasting in this extraction process has been identified as a significant source of environmental pollution and vegetation destruction, resulting in irreversible impacts on ecology and the environment [3]. In response to these environmental concerns, researchers are exploring alternative materials to replace natural aggregates in concrete production. These alternatives encompass a range of recycled materials, such as foundry mold waste [4–7], glass waste [8–10], plastic waste [11,12], fly ash [13,14], tire waste [15,16], construction and demolition wastes (CDWs) [3,17–20], etc.

Within the construction sector, CDWs are generated during the construction and demolition phases of buildings. The three major CDW-producing countries or regions include China, producing approximately 2.3 billion tons/year [21], the United States, producing 600 million tons in 2018 [22], and the 28 EU countries, totaling 807 million tons in 2020 [22], respectively. CDWs mainly consist of concrete, mortar, ceramic, brick, metal, plastic and more. Searching "construction and demolition wastes" keywords through the Scopus database, a total of 5779 articles have been published from 2000 to 2023 [23]. As shown in Figure 1, studies on "Construction and demolition waste" are mainly concentrated on the performance of materials with CDW and waste management. There are some studies relating to one type of CDW. In Figure 2, it can be seen that the country that has published the most articles about CDW is China, followed by Australia, Spain, England and Portugal, etc. This is basically positively related to the CDW output in these countries. However, from the perspective of the CDW resource utilization rate, the CDW resource utilization rate in developed countries is higher. As can be seen in Figure 1, developing countries such as China and India have paid attention to research on CDW to improve the resource utilization rate of CDWs.

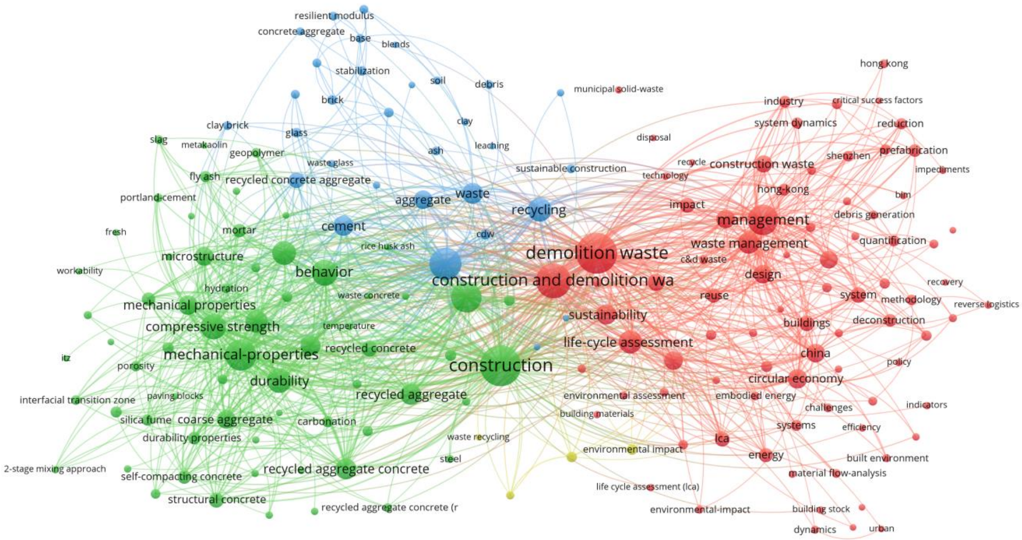

Figure 1. Studies related to "Construction and demolition waste".

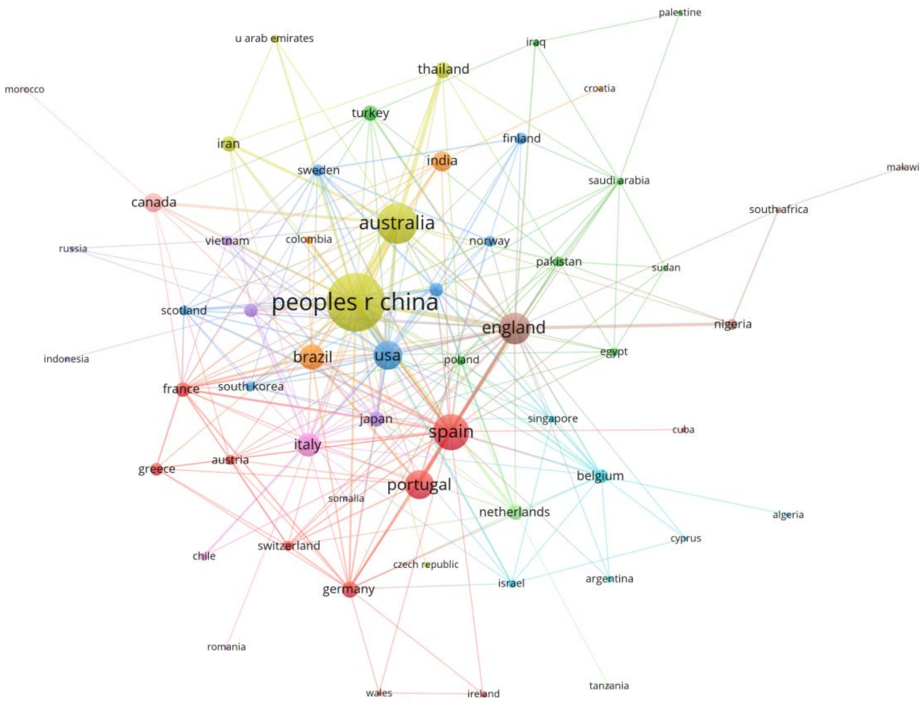

Figure 2. The distribution of articles published worldwide from 2000 to 2023.

Generally, CDWs are considered as inert solid waste and can be used in concrete [3,24–27], mortar [28–30], bricks [31,32], blocks [33,34], mountain landscaping [35], etc., according to the different size distributions of CDW. Additionally, some glass waste [36,37] and plastic waste [38,39] have been used in concrete. Zhang et al. [40] studied the status of CDWs in China; CDWs could occupy a volume of 7.5 billion m^3, and the potential recycling value of CDWs was up to USD 401 billion in 2013. In addition, using CDWs as a replacement for natural aggregates for concrete construction could save 10–20% of the material cost. Therefore, effectively managing and repurposing this substantial volume of CDWs is imperative. Simultaneously, researchers are directing their efforts towards enhancing concrete performance and reducing costs through the incorporation of CDWs in construction. For instance, Allali et al. [41] conducted a study on the application of 60% recycled concrete aggregate (with a size of 4.75–19 mm) and 40% sand (with a size of 0–2.36 mm) as a sub-base material for roads. In a related context, Jia et al. [3] took advantage of the porosity of CDWs and developed a thermal concrete incorporating demolition waste, with a size range of 4–10 mm, and paraffin. The incorporation of demolition waste not only addresses the environmental concerns associated with CDWs, but also contributes to the development of innovative materials. Güneyisi et al. [42] studied the rheological and fresh properties of concrete with the incorporation of recycled coarse and fine aggregates. The results showed that when the recycled coarse aggregates were used, the slump of concrete decreased. Based on different contents of coarse aggregate, 25%, 50%, 75% and 100% fine aggregate were added, respectively, to replace river sand, and the slump of concrete increased. Additionally, during the CDW recycling process, aggregates with different particle sizes are produced. Singh et al. [25] and Weibo Consulting [43] noted that a well-established technical foundation and industrialization have been achieved in the realm of recycled coarse aggregate; however, there remains a dearth of technologies for recycled fine fractions, which constitute more than 40% of the total recycled material. Although some research has proved that recycled concrete could obtain certain material properties when incorporating an amount of CDWs, recycled aggregate is typically inferior to natural aggregate in its concrete material properties. At present, some studies, including parametric and numerical studies with empirical studies, have been conducted to investigate the reason why the performance of recycled aggregate is worse than that of natural aggregate [44,45], and the relationship between the properties of CDWs and those of recycled concrete material has been established. Zhang et al. [46] proposed an integrated interface parameter to reveal why recycled concrete is inferior to natural concrete on a microscale and macroscale, and connect the interface properties and the macro material properties. Moreover, Gong et al. [47] also performed a mesoscale discrete analysis of the mechanical properties of recycled aggregate, and proposed an empirical model to predict the compressive strength of recycled aggregate concrete using a database of simulation results obtained by RBSM. In addition to the above studies, new intelligent technologies has been adopted to research the performance of recycled concrete. Wang et al. [48] systematically reviewed the applicability and reliability of AI technologies in the field of sustainable concrete properties, and found that AI technology can effectively evaluate the mixture schemes, static properties and durability of sustainable concrete; the reason for this is that it has a stronger nonlinear processing ability. However, more progress is needed in order to accurately predict the performance of concrete in the future.

Additionally, numerous researchers have studied the different types of aggregate used in concrete. For example, Jia et al. [4] investigated the replacement of lightweight aggregate with foundry mold waste in concrete. The results showed that the mechanical performance and durability of the lightweight concrete was improved. Omoding et al. [9] studied the effect of using recycled glass waste as a coarse aggregate on the concrete; the experimental results showed that when the replacement of coarse aggregate with recycled glass waste was less than 25%, the abrasion resistance of the concrete was not affected, and the concrete produced with the 100% recycled waste glass aggregate had the same abrasion resistance as the concrete incorporated with 100% crushed limestone coarse aggregate. Basha et al. [12] evaluated the possibility of using recycled plastic waste as a substitute for natural aggregates in concrete; they developed a lightweight concrete with a unit weight of 1500 kg/m^3 and a compressive strength of 17 MPa by using 100% recycled plastic aggregate, and they discovered that the flexural strength, modulus of elasticity and bond strength of the RPA concrete decreased with an increasing quantity of RPA. Kazmi et al. [15] studied concrete that incorporated waste tire rubber and recycled aggregates by adopting a new compression approach; the results showed that the compressive strength and elastic modulus of the compressed RAC and treated RAC containing 10–20% CR were close to those of traditional concrete without CR.

Furthermore, Mohmmad et al. [49] studied the properties of concrete blocks that used different agricultural wastes as sand substitutes in rural areas of India; they discovered that cement blocks containing coconut husks and pistachio shells exhibit acceptable strength and durability. Sathvik et al. [50] investigated the effects of an alkali activator on the fly ash reaction and the performance of geopolymer concrete; the results showed that with an increase in the curing temperature and alkaline solution concentration, the compressive strength of geopolymer concrete mixed with fly ash continues to increase. Mohmmad et al. [51] studied the post-fire mechanical performance of concrete with the incorporation of waste EPS. The result showed that the concrete containing different proportions of EPS had an increased post-fire compressive strength compared with traditional concrete. Besides that, there are also some studies on the substitution of cementitious materials [52]. Mohmmad et al. [53] proved that metakaolin-based geopolymer concrete, which is a current sustainable alternative to cement, could use nano-silica to improve its mechanical performance; they found that metakaolin (MK)-based GC with the incorporation of 6.0% NS produces the highest mechanical properties.

Tables 1 and 2 review some works about the recycled coarse and fine aggregates used in concrete.

Table 1. Articles about the replacement of recycled coarse aggregates with natural aggregates.

Study	Recycled Coarse Aggregate				Replacement Level	Cement	Slump	Compressive Stength		
	Type	Size	Density	Water Absorption		Type		7 Days	28 Days	90 Days
		mm	kg/m^3	%	%		cm	MPa		
Majhi et al. [54]	Concrete	20	2530	4	0	OPC	70	28.37	37.77	46.1
					25		75	27	36.5	45
					50		85	25	33.5	41.85
					100		95	22.5	30.5	37.68
Simsek et al. [55]	Concrete	4–11.2	2420	4.79	20	CEM I 42.5R	80	22	27	34
					40		75	23	25	33
		11.2–22.4	2380	4.96	60		70	22	24	33
					80		65	21	23	29
					100		60	18	23	27
Delsaute and Staquet [56]	Demolition concrete waste	4–10 10–20	2340 2320	/	0 30 100	CEMII/A-L 42.5 R	29 27 23	40 26 25	/ / /	/ / /
Pedro et al. [57]	LC—laboratory-produced concrete	/	2300	3.6	0	CEM I 42.5R	13.5	65.4	72.6	74.3
					25		13.2	59.8	68.2	72.1
					50		13.5	58.8	66.5	69.0
					100		12.8	55.5	61.2	64.3
					100F		12.7	53.9	65.4	68.3
					100C		13.2	59.3	68.7	71.8
	RW—real concrete wastes	/	2400	3.9	25		13.8	58.7	68.9	72.3
					50		13.6	54	63.8	67.2
					100		13	52.9	61.0	64.7
					100F		13.7	50.9	61.5	64.8
					100C		13.4	58.9	66.9	70.0

Table 1. *Cont.*

Study	Recycled Coarse Aggregate				Replacement Level	Cement	Slump	Compressive Stength		
	Type	Size	Density	Water Absorption		Type		7 Days	28 Days	90 Days
		mm	kg/m^3	%	%		cm	MPa		
Bogas et al. [58]	RHD: structural concrete	4–11.2	1735	15.7	0 20 50 100	CEM I 42.5 R	13 12 13 12.5	32.8 33.9 34.4 36.1	38.4 40.4 43.1 43.7	39.3 41.3 46.8 48.5
	RM: a no-fines non-structural lightweight concrete		878	24.9	0 200 50 100		12.5 13 13 12.5	16 21.6 23.8 27.7	19.2 25.1 27.7 33.4	20.7 26.5 30.5 34.6
Kou et al. [59]	Low-grade construction and demolition waste	RAI: 5/10	2263	6.25	0 20	OPC	/	32.5 29.3	43.4 39.4	47.8 44.2
		RAI: 10/20	2302	6.18	50 100			28.4 20.4	37.8 27.9	42.4 33.8
		RAII: 5/10	2315	5.81	0 20			32.5 30.4	43.4 39.7	47.8 43.6
		RAII: 10/20	2242	5.49	50 100			26.2 24.5	33.9 32.3	39.6 36.8
		RAIII: 5/10	2490	4.26	0 20			32.5 29.1	43.4 45.3	47.8 49.1
		RAIII: 10/20	2580	3.52	50 100			27.6 24.4	42.5 38.1	47.5 45.5
Bendimerad et al. [60]	Concrete waste	4–10	2.34	5.3	0 30	CEM II/A-L 42.5	195 193	23 22.1	31.4 28.5	/ /
		10/20 mm	2.32	4.9	0 100		204 222	19.4 12.2	29 24	/ /
Güneyisi et al. [42]	Recycledconcrete aggregates	/ / /	2360 2310 2260	/ / /	0 50 100	OPC	70 72 71.5	/ / /	/ / /	/ / /
Singh and Singh [61]	Concrete wastes	Fineness modulus 6.88	/	5.65	0 25 50 75 100	OPC	68.5 68.5 68.8 68.4 68	40 36.9 34.8 33 33	42.5 40 37 35 34	43.8 42 40 35.2 35.3
Rao et al. [62]	Demolished RCC culvert, 15 yearsold	4.75–20	1413	/	0 25 50 100	OPC	57.5 55 50 50	/	50 46 44 42	/
Suhaib et al. [63]	Demolished bridge	/	/	6.05	0 30 50 70	OPC	77 67 59 46	16.25 14.64 15.21 14.67	29.3 26.2 27.31 23	/
Kazmi [38]	Recycled aggregate	max. 20 mm	1414	6.85	0 10 20	OPC	/ / /	/ / /	18.92 17.65 16.01	/ / /
Basha et al. [39]	Recycled plastic aggregate	5–10 mm	980	0	0 25 50 75 100	OPC	/ / / / /	/ / / / /	46.8 35 26 19 17	/ / / / /
Mohammed et al. [51]	EPS waste	5 mm	/	/	0 15 25 50	OPC	128 95 83 105	/ / / /	19.94 19.29 16.8 17.66	/ / / /

Table 2. Articles about the replacement of recycled fine aggregates with natural aggregates.

Study	Recycled Fine Aggregate				Replacement Level	Type Cement	Slump	Compressive Strength		
	Type	Size	Density	Water Absorption				7 Days	28 Days	90 Days
		mm	kg/m^3	%	%		cm	MPa		
Evangelista and Brito. [64]	Concrete	FM:2.387	dry: 1913	13.1	0 30 100	CEM I 42.5R	8 ± 1		59.3 57.3 54.8	/ / /
Farah et al. [65]	Concrete	150 µm–1.18 mm	2340	5.3	0 10 20 30 40	CEM I 42.5R	15 15 12 10.5 8.5	40 42 48 46.5 45	48.53 49.74 50.68 48.47 45.28	/ / / / /
Singh et al. [25]	Concrete					CEM I 42.5R	20 mm	water/cement ratio	SP content (%)	
		0–45 µm	/	replace cement replace cem. and sand	0 15% 30% 30%			0.36 0.36 0.36 0.36	2.16 2.84 3.52 2.5	/ / / /
		0.15-4.75 mm	2199	12.57 (replace sand)	25% 50% 75% 100%			0.38 0.39 0.41 0.42	2.65 3.3 4.24 6.11	/ / / /
Revilla-Cuesta et al. [66]	Concrete	0–4 mm	2370	7.6	0 25 50 75 100	CEM I 52.5 R	68 69.5 73 74 75.5	56 53 40 30 25	60 55 44 31 29	60 58 43 33 32
Simsek et al. [55]	20 MPa Concrete	0–4 mm	2430	4.6	20 40 60 80 100	CEM I 42.5R	8 7 6.5 5 4	21 20 19 16 13	24 22 1 21 19	33 30 28 24 21
Delsaute and Staquet [56]	Recycled demolition concrete	0–4 mm	2100	10.65	0 30	CEMII/A-L 42.5 N	/ /	29 23	40 36	/ /
Bogas et al. [67]	Fine recycled aggregate	0–4 mm	2156	9.05	0 20 50 100 0 20 50 100	CEM I 42.5R (350 kg/m^3) CEM I 42.5R (420 kg/m^3)	11.5–12.5 11.5–13.5	/ / / / / / / /	51.7 49.9 47.4 43.1 81 72.7 67.4 58.8	/ / / / / / / /
Evangelista and Brito [68]	Fine recycled concrete	Sand equivalent: 69	Dry: 2000	10.43	0 10 30 50 100	CEM I 42.5R	S3	/	33.6 32.1 32.7 32.8 30.7	/
Lyo et al. [69]	Brick sand	Fineness modulus: 1.2	2360	36.5	0 50 100 0 50 100 0 100 0 100	/	/	/	49.1 42.9 34 59.1 49.2 44.5 56.4 42.1 50.7 33.1	/

Table 2. *Cont.*

Study	Recycled Fine Aggregate				Replacement Level	Type Cement	Slump	Compressive Strength		
	Type	Size	Density	Water Absorption				7 Days	28 Days	90 Days
		mm	kg/m³	%	%		cm	MPa		
Geng and Sun [70]	Recycled aggregate	FM: 2.8	/	1.6	0	/	18.3 (water: 155 kg/m³)		46.7	/
					20		15.4 (water: 155 kg/m³)		44.5	
					40		8.9 (water: 155 kg/m³)		38.2	
		FM: 2.7		7.5	60		5 (water: 155 kg/m³)		31.2	
					80		/(water: 155 kg/m³)		21.5	
					20		19.3 (water: 167 kg/m³)		43.3	
					40		18.6 (water: 179 kg/m³)		34.6	
					60		18.1 (water: 194 kg/m³)		29.8	
					80		17.4 (water: 234 kg/m³)		20.2	
		FM = 2.9		6.8	40		10.5 (water: 155 kg/m³)		39.6	
		FM = 3.3		5.9	40		18.2 (water: 155 kg/m³)		42.1	

This work reviewed the methods used to recycle CDW and the physical properties of coarse and fine CDW. The research on recycled coarse and fine aggregates in concrete was discussed with regard to physical properties (density, water absorption), mechanical properties (compressive strength, flexural strength) and durability (chloride ion penetration and resistance carbonation). In conclusion, the exploration of recycled materials, especially CDWs, as alternatives to natural aggregates in concrete production is gaining momentum. The cited examples highlight the promising outcomes of research endeavors in this direction, emphasizing the need for sustainable practices in the construction industry. Additionally, the analysis of different CDW particle sizes contributes valuable insights to the tailoring of concrete formulations for specific applications, balancing environmental considerations with performance requirements.

Methodology of the Review Paper

The methodology used to create this review prioritized papers published within the last 20 years based on their contribution to the topic and scientific relevance. Scientific papers were selected by considering their impact and relevance. The search for papers was conducted using internationally recognized databases including SCOPUS, Web of Science, and open access databases.

In response to the growing interest among researchers in Construction and Demolition Waste (CDW), this comprehensive review critically examines the methodologies used for recycling CDW, evaluates the properties of recycled aggregates (including structure, density, water absorption, etc.), investigates the diverse applications of recycled aggregates, and assesses their impacts on the physical properties, mechanical properties, and durability of concrete. By synthesizing a multitude of technical studies, this review aims to provide readers with a nuanced understanding of the implications of utilizing recycled aggregates in cement-based materials, offering valuable insights for the advancement of sustainable construction practices.

2. CDW Recycling Process and Properties of CDW

2.1. CDW Recycling Process

Currently, there are various buildings with different forms, structures and materials in different regions and countries, resulting in the generation of a large number of different types of construction waste. Studies from researchers worldwide have shown that many construction and demolition wastes are mainly composed of concrete, mortar, bricks, plastic, glass, paper, wood, and metal [71–74]. And in order to utilize these construction wastes as resources, two main CDW recycling processes that transform demolished materials into a smaller-sized fraction are applied, namely mobile recycling machinery and fixed recycling plants [75–77].

Mobile recycling machinery can handle CDW on-site, then the recycled aggregates can be directly utilized without the need for additional transportation. However, the quality of the aggregates is not high, and the separated aggregates generally contain various types of waste materials that are not fully processed, most of which are only used for landfill [22,78]. Figure 3 presents the mobile recycling machinery process for RAs, which has three steps [79]: (1) feed inlet section: pre-sorting the CDW to separate out the waste that cannot be processed by machines or contains contaminated elements, and sending usable raw materials to the feed port; (2) crushing section: crushing and magnetic separation: reducing the RA size and removing the remaining ferrous; (3) screening and output section: separating the aggregates using a comprehensive screening platform into different size fractions for various applications: small size (0–5 mm), medium size (5–20 mm), large size (20–40 mm). It is worth mentioning that aggregates larger than 40 mm should be further crushed in step until the aggregates meet the particle size requirements.

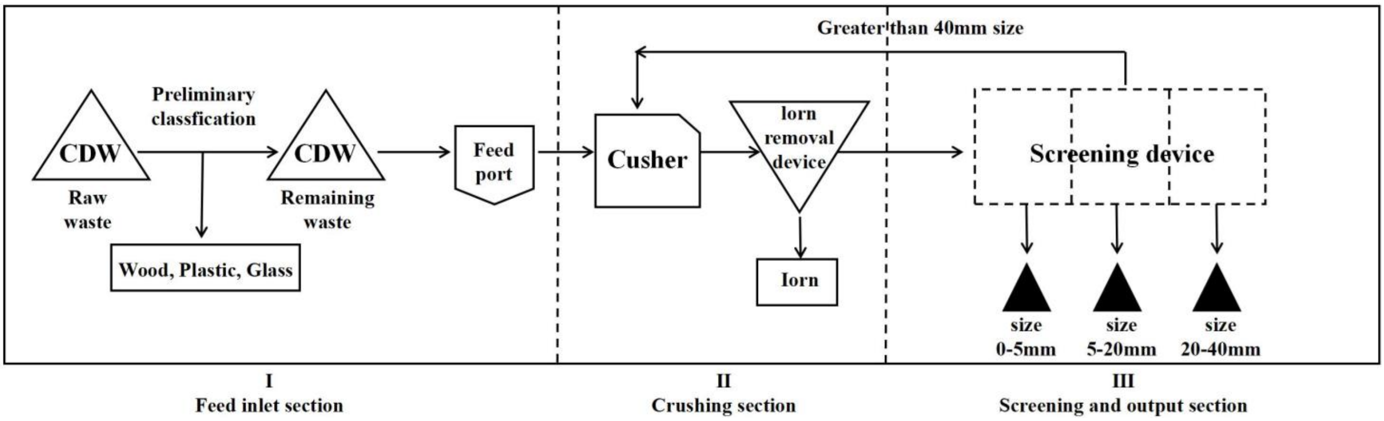

Figure 3. Schematic diagram of mobile CDW recycling process.

Compared to recycling machinery, fixed recycling plants have stronger processing capabilities and the processed aggregates are of a higher quality than those processed by mobile recycling machinery through repeated sorting, crushing, and separation. Specifically, the processed aggregates' impurity content is less, they exhibit better soundness, and they also better satisfy the particle size requirements. Figure 4 presents the working process of a fixed recycling plant, which has four steps: (1) preliminary treatment: feed port process, removal of soil, preliminary crushing, magnetic separation: feed waste, removal of small particles and remaining ferrous, reduction in the size of the waste; (2) manual sorting: removal of large pieces of steel, wood, plastics or paper that could influence the quality of the recycled aggregate, mainly through manual sorting; (3) secondary crushing: secondary crushing to further reduce the size of the waste and remove the remaining ferrous; (4) finished product screening: separating the aggregates for various applications: small size (0–5 mm), medium size (5–10 mm, 10–20 mm, 20–31.5 mm), large size (more 31.5 mm). It is worth mentioning that large aggregates should be further crushed in step

3 until they meet the particle size requirements [80]. Table 3 shows a comparison of two different CDW recycling processes.

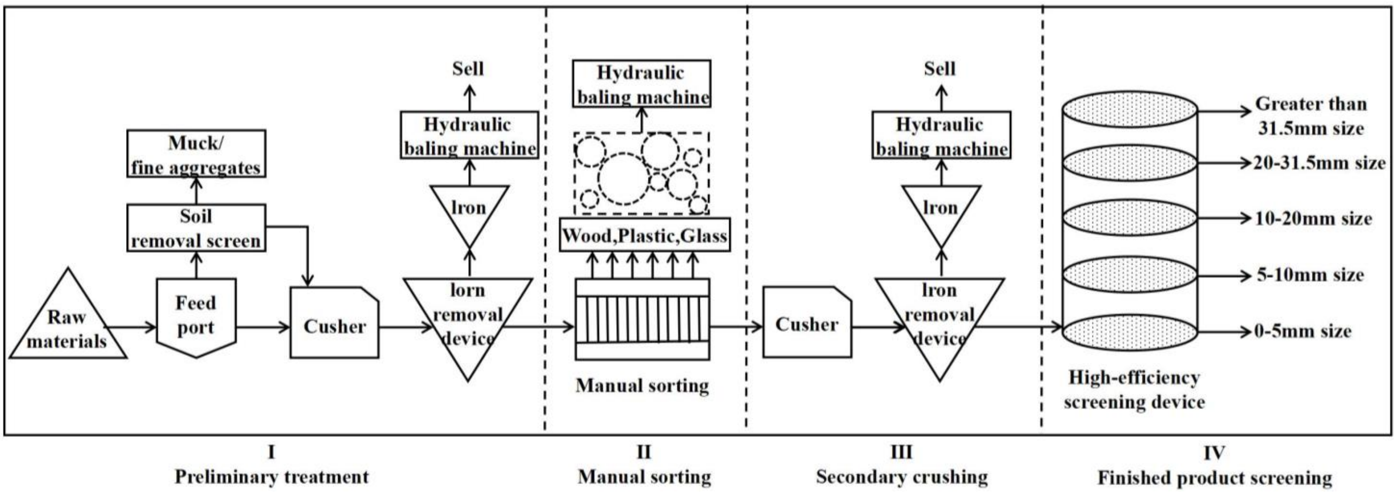

Figure 4. Schematic diagram of mobile CDW recycling process.

Table 3. Comparison of two different CDW recycling methods.

	Mobile Recycling	Fixed Recycling
The level of the recycling process	simple	complete
Types of equipment included	few	many
Output production forms	single	various
The level of production cost	moderate	high
The quality of the recycled aggregates	low	high
The scope of application	small	large

Furthermore, according to the above two types of construction waste treatment process, it is clear that both recycling methods involve multiple processes of crushing, separating, and removing impurities, and the research demonstrates that the process of crushing, separating and removing impurities could directly affect the quality of the recycled aggregate [81,82]. Wan et al. [83] found that with an increase in the crushing and separation times, the content of small-sized aggregate increases, the density of the aggregate increases, and the water absorption of the aggregate decreases. Therefore, the quality of the recycled aggregate has been improved.

However, compared to natural aggregate, the quality of recycled aggregate is still poor, with a lower density and higher water absorption [84–86]. Therefore, scholars have further searched for the reasons for the poor quality of recycled aggregates; one of the reasons is that the surface of the recycled aggregate still adheres to the original mortar after multiple crushing and separation processes [87], and researchers have found that there is a very strong correlation among the adhered mortar, water absorption and density.

Besides that, numerous researchers are also seeking methods to remove adhered mortar and improve the quality of recycled aggregate, such as heat and rubbing, eccentric rotary grinding, screw grinding, rotary drum mills [88], acid, ball milling [89], microorganisms [90] and RA carbonation [91]. Kim et al. [92] proposed an approach that used a steel ball as a mechanical method and acid as a chemical method to remove paste from the surface of origin fine aggregate, and the experimental results showed that the oven-dry density and absorption ratio were 2.51 g/cm^3 and 2.3%, which satisfied the quality criteria of over 2.2 g/cm^3 and under 5%, respectively. Cho et al. [93] investigated the change in a recycled fine aggregate after the use of microbial carbonate precipitation as a microbial modification. They found that the surface of the RFA was covered with calcium carbonate precipitate, which contributed to an increase in the recycled fine aggregate weight and a reduction in the recycled fine aggregate water absorption under the proposed conditions.

In general, the recycling process affects the quality of recycled aggregate, and it is necessary to improve the recycling equipment and methods in the future; it is worth mentioning that in the CDW recycling process, be it within the domain of stationary or mobile recycling operations, the treatment of construction and demolition waste needs a meticulous treatment that comprises sorting, crushing, and screening processes. Within this procedural framework, a consequential phenomenon emerges: the augmentation of cracks; this culminates in the elevation of its porosity or water absorption capacity. Such a consequential effect is subject to meticulous scrutiny and discourse in the elucidative confines of Section 2.2.

2.2. Properties of Recycled Aggregates

2.2.1. The Shape and Distribution of CDW

After the CDW experienced a series of crushing processes, coarse and fine aggregates of different particle sizes were obtained. Its particle shape was quite different from that of natural aggregates. For example, the shape of natural aggregates is rounder and less sharp. The recycled coarse aggregate (RCA) contains fewer needle flakes than natural aggregates. This is mainly affected by the collision, peeling during the crushing process and the location of the broken face. Due to the influence of the rock structure, the fracture surface of natural aggregates is usually located within the rock, while the recycled aggregates are in the cement mortar layer, dispersing the stress points within the rock. This makes it easier for the aggregates to achieve a rounder shape, resulting in a lower content of needle-like particles [71].

The surface of recycled aggregates typically exhibits a rough and irregular shape, characterized by numerous corners and a slightly flat profile. Additionally, the impact of mechanical crushing causes damage to the recycled aggregate, resulting in the formation of multiple internal microcracks within the aggregate [94,95] (see Figure 5). The formation of microcracks in aggregates is attributed not only to the compression and collision during the process of crushing waste concrete, but is also potentially influenced by various factors, such as an alkali–aggregate reaction occurring within the original waste concrete structures or components prior to their dismantlement [94].

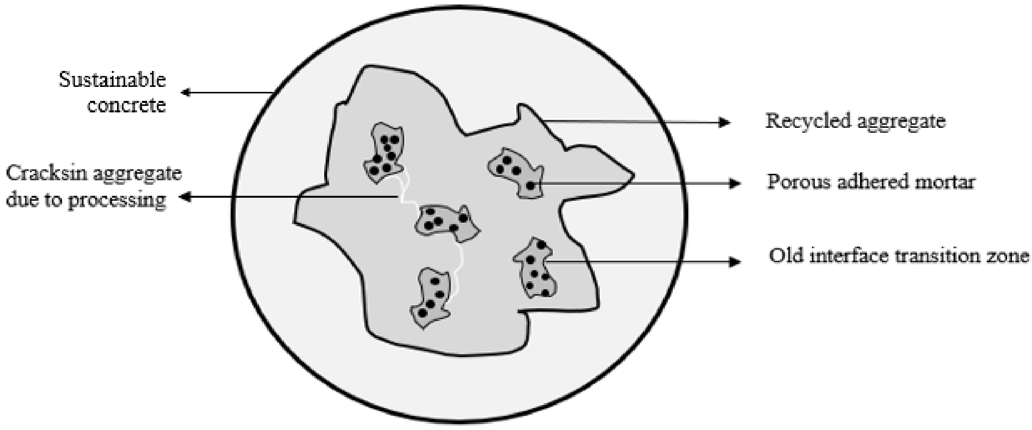

Figure 5. Pictorial representation of recycled aggregates.

Gorjinia et al. [96] obtained recycled concrete aggregates from crushing-tested reinforced concrete beams in the laboratory. The surface structure of the natural and recycled aggregates was then observed, and the microscopic surface structure was observed under an electron microscope. The results demonstrated that the surface roughness of recycled aggregates is higher than that of natural aggregates due to the presence of old bonding mortar or unhydrated cement slurry on their surface, which are loosely connected and not tightly bonded. Additionally, there were significant voids and large pores in the recycled aggregate, resulting in increased porosity. For instance, during the process of crushing construction and demolition wastes, the separation between the aggregate and mortar leads to the formation of pores on the surface of the aggregate.

Compared to recycled coarse aggregate, recycled fine aggregate possesses a smaller particle size, thereby harboring a greater proportion of weathered cement mortar and fissures. Consequently, its microstructure becomes more intricate in comparison to that of recycled coarse aggregate, inevitably exerting an influence on the microstructure and overall performance of recycled aggregate concrete.

Since the structure of recycled aggregate, such as its number of pours, adhered mortar, interface transition zone and cracks, the concrete interiors become complex. Additionally, these are important factors that influence the physical, mechanical and durability properties of concrete.

2.2.2. Density and Water Absorption of CDW

Density refers to the mass of particles per unit volume of matter. It is one of the basic characteristics of materials, and has an impact on the mechanical properties, physical properties, durability and other aspects of materials. According to the Chinese standards GB/T 25177-2010 [97] and GB/T 25176-2010 [98], the types of recycled coarse and fine aggregates used in concrete are divided into classes I, II and III. Tables 4 and 5 show the density-based classification criteria.

Table 4. Density of regenerated coarse aggregate.

Parameter	Class I	Class II	Class III
Density (kg/m^3)	>2450	>2350	>2250

Table 5. Density of recycled fine aggregate.

Parameters	Class I	Class II	Class III
Density (kg/m^3)	>2450	>2350	>2250
Loose bulk density (kg/m^3)	>1350	>1300	>1200

However, standard GB/T 14685-2022 [99] specifies that the density should not be less than 2600 kg/m^3 for pebble and crushed stone for construction. The standard GB/T 14684-2022 [100] stated that the density of sand should not be less than 2500 kg/m^3, and that the loose bulk density should not be less than 1400 kg/m^3. Compared with natural aggregates, the density of recycled aggregates is lower than natural aggregates, mainly because the porous structure of recycled aggregates reduces the density. In addition, the density of recycled aggregate is also related to the strength grade and formulation of the concrete, and the usage time, usage environment and region of the recycled aggregate matrix concrete [101].

Gorjinia et al. [96] reported that recycled aggregate is about 20% lighter than normal aggregate. The reason for this is the old mortar being attached to the normal aggregate. And the density of recycled aggregate decreases as the strength of the parent concrete decreases, or as the recycling cycles of the recycled aggregate increase. Xu [102] studied the density of recycled aggregate, and the results showed that the density of recycled aggregate could not reach the standard of natural aggregate. However, recycled aggregate could reduce the weight of structures due to its low density, which is conducive to earthquake resistance. Zhu et al. [103] reported that the quality of a third-generation recycled aggregate was inferior to that of natural aggregate, and the quality decreased as the number of cycles increased. This can be explained by the fact that, with the increase in the number of recovery cycles, the content of mortar adhered to the recycled aggregate is higher, which also determines the difference in the other physical properties of recycled aggregate.

Water absorption refers to the quantity of water absorbed per unit area and per unit of time, and it is one of the important indexes used to evaluate the properties of materials. Since the surface of recycled aggregates is usually wrapped with a layer of mortar, making it rougher, during the recycling and crushing process, there are many cracks inside the recycled aggregates. The water absorption of recycled aggregates is much higher than that of natural aggregates [104]. Chen et al. [105] studied the water absorption of recycled aggregates with sizes ranging from 4.75 to 31.5 mm; the results showed that the water absorption of the recycled aggregates increased as the aggregate particle size decreased. This can be explained by the specific surface area increasing as the size distribution of the recycled aggregate decreased. Zhu et al. [103] investigated whether the water absorption of recycled coarse aggregates of different generations decreases with an increase in the number of cycles. Gorjinia et al. [96] found that the water absorption of recycled coarse and fine aggregates obtained from concrete with a compressive strength of 30 MPa may be significantly higher than ordinary coarse and fine aggregates by approximately 11.5 times and 3.5 times, respectively.

In summary, the density and water absorption of recycled aggregates are closely related to the porous structure of recycled aggregates. In addition, a certain number of cracks are also caused during the process of crushing recycled aggregates, which further increases the water absorption of recycled aggregates. However, a higher water absorption rate and lower density further lead to the higher water absorption rate and lower density of recycled concrete compared with ordinary concrete. Therefore, the influence of recycled aggregate on the physical properties of concrete is discussed in detail in Sections 3.1 and 3.2.

3. Recycled Aggregates Used in Concrete

3.1. Concrete Design

The concrete mix design plays a crucial role in the field of building materials. By carefully designing the mix proportions of concrete, the optimization of concrete's material properties, such as its strength, durability, workability, and sustainability, can be achieved. Concrete mix design involves a comprehensive consideration of factors such as water-cement ratio, water-binder ratio, powder-fine aggregate ratio, aggregate particle size distribution, among others, to ensure that the workability, strength development, and durability of concrete meet design requirements [25,64–69].

In the current construction industry, there is a growing focus on exploring sustainable concrete mix design solutions. By reducing the cement content, utilizing alternative materials and additives, optimizing aggregate proportions, and employing other strategies, it is possible to decrease the carbon footprint, resource consumption, and environmental impact of concrete, thus promoting the sustainable development of concrete materials. Therefore, the concrete mix design not only aims to enhance the performance of concrete structures, but also drive the construction industry towards a more environmentally friendly and sustainable direction. Ziada et al. [106] investigated the correlation between carbon nanotubes (CNTs) and metakaolin- and slag-based geopolymers. To achieve their research objectives, geopolymer samples with CNT contents of 0%, 0.05%, 0.15%, and 0.25% were prepared and tested under three different environmental conditions. Subsequently, the compressive strength of the geopolymer samples containing 0.25% CNTs exhibited a considerable increase of 32.7% and 34.4% compared to the CNT-free geopolymer samples when immersed in lake water and seawater, respectively. Paruthi et al. [107] studied the effects of replacing cement with waste eggshells in their study. The findings revealed that substituting 20% of cement with eggshell powder resulted in an increase in concrete strength.

In the following chapters, the effects of the replacement of different components in concrete with recycled aggregates from construction and demolition waste on the physical, mechanical and durability properties of concrete are reviewed in detail.

3.2. Workability of Fresh Concrete

Workability is a critical parameter in assessing the ease with which freshly mixed concrete can be handled, placed, and compacted. The incorporation of recycled coarse and fine aggregates influences the workability of fresh concrete, and this section delves into specific aspects related to workability. Several studies have investigated the impact of recycled coarse and fine aggregates on the workability of fresh concrete. For instance, Rao et al. [62] investigated the workability of fresh concrete with the incorporation of recycled coarse aggregate. The natural aggregate, with a size ranging between 4 to 20 mm, was replaced by recycled coarse aggregates with a size ranging between 4 and 20 mm under replacement ratios of 25%, 50% and 100%. The results showed that the slump decreased with an increase in the recycled coarse aggregate content. When the recycled coarse aggregate content was 100%, the slump of fresh concrete decreased by 13%. This can be explained by the recycled aggregate having a rough surface. Zega et al. [108] studied fresh structural concretes with different percentages of recycled fine concrete aggregates (0%, 20%, and 30%). The recycled aggregate with a fineness modulus of 3.15 and water absorption of 8.5% was used. The results showed that the slump decreased with the amount of recycled fine aggregate, and that the slump of concrete with 30% recycled fine aggregate was significantly lower, although the admixture dose was increased. Combined with Section 2.2.1, this phenomenon can be explained by the shape being irregular, causing the total surface area to increase. And the friction between aggregates increased since the surface of the recycled aggregate featured more powder. Therefore, the slump of fresh concrete decreases with the recycled aggregate content. In addition, recycled aggregate has a high level of water absorption, so it is in an unsaturated state during the preparation of concrete and will absorb water effectively, thus affecting the slump of concrete.

Additionally, to enhance the workability of concrete incorporating recycled aggregates, researchers have proposed various strategies, including optimizing the grading of recycled aggregates, adjusting the water/cement ratio, and incorporating chemical admixtures. For example, Zheng et al. [109] studied the gradation curve of a recycled coarse and fine aggregate, which was not fine enough according to the present codes; the gradation modification was a way to optimize the gradation curve of the recycled coarse and fine aggregate, and the respective bulk density was increased and the crushing index was reduced. In addition, the variability in the concrete increased when the recycled fine aggregate replacement ratio increased from 0 to 30%.

Cartuxo et al. [110] adjusted the water/cement ratio to optimize the slump of fresh concrete with the incorporation of recycled fine aggregate. The water/cement ratio was adjusted to achieve a similar slump of 125 $\pm$ 15 mm in concrete with a different percentage of recycled fine aggregate. When the 100% recycled fine aggregate was substituted for the natural aggregate in concrete, the water/cement ratio increased by 17.6% compared to the control concrete. Sasanipou an Aslani [111] investigated the effect of superplasticizer on the slump of fresh concrete with the incorporation of fine and coarse recycled concrete aggregates. As the recycled coarse aggregate content increased from 0 to 100%, the quantity of superplasticizer increased by 11%, keeping within the range of 590–610 mm. Furthermore, the replacement of natural fine aggregate with recycled fine aggregate in concrete was evaluated. When the concrete incorporated 100% recycled fine aggregate, the slump flow increased by 4 mm and the quantity of superplasticizer decreased by 16.7%. This is because the addition of superplasticizer makes the arrangement between water molecules and cement molecules more orderly, thereby increasing the slump of fresh concrete. Jia et al. [3] evaluated the adsorption of paraffin by recycled aggregate. After absorbing paraffin, the surface of the recycled aggregate was smooth and clean, which also improved the slump of the fresh concrete.

In summary, the workability of fresh concrete is a crucial aspect affected by the incorporation of recycled coarse and fine aggregates. Understanding the specific factors influencing workability and adopting suitable measures to enhance it are essential for the successful application of sustainable concrete in construction projects.

3.3. Density and Water Absorption of Concrete with CDW

Density and water absorption are physical characteristics of concrete. Aggregates occupy most of the volume of concrete, which has a great influence on the density and water absorption of concrete. Tables 1 and 2 review numerous studies, and the high water absorption and low density of recycled aggregate are shown. This section studied the effect of the density, water absorption by immersion and water absorption by capillarity on the concrete with the incorporation of recycled aggregate. Bendimerad et al. [60] studied the density and water absorption of concrete with different recycled coarse and fine aggregate replacement rates. As the recycled aggregate content increases, the density decreases and water absorption increases. Bogas et al. [67] investigated the use of fine recycled concrete aggregates in concrete. The results showed a higher porosity, lower density, and higher water absorption compared to normal concrete. Shi et al. [112] evaluated the replacement of natural aggregate with recycled concrete aggregate in concrete. The results indicated the correlation between the porosity of recycled aggregates and the early-stage water absorption of concrete. Nedeljkovi et al. [113] proposed that the water absorption and density of recycled aggregates are the key parameters in mortar and concrete design. The work determined the water absorption over time and measured the total water absorption capacity of the fine recycled concrete aggregates (FRCAs). By observing the evolution of the water content of the cement slurry, it was found that the water absorption of the FRCSs in the slurry was lower than that in water. This can be explained by cement grains having a great advantage regarding the content of water; therefore, it is difficult for FRCAs to reach their maximum absorption capacity during mixing.

On the other hand, water absorption by capillary is a specific aspect of water ingress that is related to the porous structure of concrete. Cartuxo et al. [110] found that the water absorption by capillary action in a 72 h test increased by up to 45%. The capillary water absorption increased with the incorporation of a fine recycled concrete aggregate. Pedro et al. [57] noted that with an increase in the recycled aggregate content, the initial water absorption by capillary increased rapidly and that the final quantity of water absorbed was higher. Bao et al. [114] indicated that the water absorption by capillarity for recycled aggregate concrete increases with an increase in the recycled aggregate replacement ratio and stress level. Gao et al. [115] investigated the capillary absorption behavior of recycled aggregate concrete using different recycled coarse aggregate replacement ratios, namely 0%, 33%, 66% and 100%. The results revealed that the amount of absorbed water increases with the increase in the time spent in contact with water; the capillary absorption coefficient increases by 19% as the recycled coarse aggregate content increases from 33% to 100%. The reason for this is that recycled aggregate concrete contains old mortar and interface transition zones, causing the higher porosity of concrete.

In summary, the above studies further prove that the factors affecting the density and water absorption of recycled concrete are mainly the low density and higher water absorption of recycled aggregates. A comprehensive understanding of the performance of recycled aggregate concrete can help develop strategies to optimize concrete design and improve its sustainability and durability.

3.4. Compressive Strength

Compressive strength serves as a vital indicator of the structural integrity of concrete and is a primary consideration in assessing the feasibility of incorporating recycled coarse or fine aggregates. Usually, cube or cylinder specimens are evaluated in a universal press, as shown in Figure 6. In concrete, there are many factors that influence their compressive strength, such as the cement content, water/cement ratio, quality of the aggregate and concrete design, etc. Tables 1 and 2 present some results regarding the incorporation of recycled aggregate in concrete.

Figure 6. Demonstration of the compressive strength test.

In this section, the recycled aggregate used in concrete is reviewed to find the effect that the compressive strength has on different quantities of recycled concrete. Thomas et al. [116] studied the effect of the compressive strength of concrete on the recycled concrete coarse aggregate content under different water/cement ratios (W/C ratio) and cement contents. The results showed that when maintaining the same W/C ratio and cement content, the compressive strength decreases as the content of recycled aggregate increases. When the W/C ratio decreased or cement content increased, the compressive strength was optimized. However, the compressive strength of concrete with the incorporation of 100% recycled aggregate increased 34% when the W/C ratio decreased by 20% and the cement content increased by 50%. Hamadand et al. [117] has carried out compressive strength tests for high-strength concrete with the incorporation of recycled coarse aggregate. The results showed that the recycled aggregate content in high-strength concrete caused an average reduction in the compressive strength of 9.8%. This can be explained by the recycled aggregate content increasing the porosity of the concrete. Farah et al. [65] evaluated the replacement of natural sand aggregate with recycled fine aggregate in concrete under replacement rates of 0%, 10%, 20%, 30% and 40%. The results showed that the use of 20% recycled aggregate in concrete could achieve the highest compressive strength compared to normal concrete.

Researchers have investigated the compressive effect of concrete made with recycled aggregate on the pre-treatment and curing of recycled aggregate. Taner et al. [118] studied the effect of internal curing on the performance of concrete containing recycled aggregates. Semi-saturated and saturated fine recycled concrete aggregates were used. The results showed that the use of saturated or semi-saturated RCAs in concrete had a positive impact on its durability through internal curing. Haghighatnejad et al. [119] reported that the compressive strength of concrete made with recycled fine aggregate has an effect on different curing conditions (continuous water curing, continuous open-air curing and continuous laboratory curing). The results showed that continuous water curing is the most suitable curing condition for concrete with the incorporation of recycled aggregate since it has a higher porosity. In addition, Li et al. [120] studied the use of waste EPS as an aggregate in concrete. In order to obtain lightweight geopolymer composites with higher strength, a new commercially available expanded polystyrene coated fiber-reinforced epoxy resin was used as a lightweight aggregate for mixing lightweight geopolymer composites in order to improve the strength of concrete. Figure 7 shows the trends observed in the compressive strength by various researchers with different replacement ratios of recycled aggregate.

Based on the aforementioned studies, it can be concluded that the application of recycled aggregate in concrete significantly impacts the compressive strength performance. Generally, the optimization of the compressive strength in concrete can be achieved through a decrease in the water/cement ratio or an increase in the cement content. However, an increase in the recycled aggregate content may affect the compressive strength of concrete, primarily due to the increased porosity caused by the recycled aggregate. Some studies have shown that the use of an appropriate amount of recycled aggregate can result in a comparable or even higher compressive strength than normal concrete. Furthermore, the proper pre-treatment of recycled aggregate and adequate curing have a positive influence on the compressive strength of concrete, such as enhancing its durability through internal curing. Therefore, integrating the findings of various researchers, it can be inferred that the application of recycled aggregate in concrete holds feasibility and potential for enhancing the compressive strength of concrete.

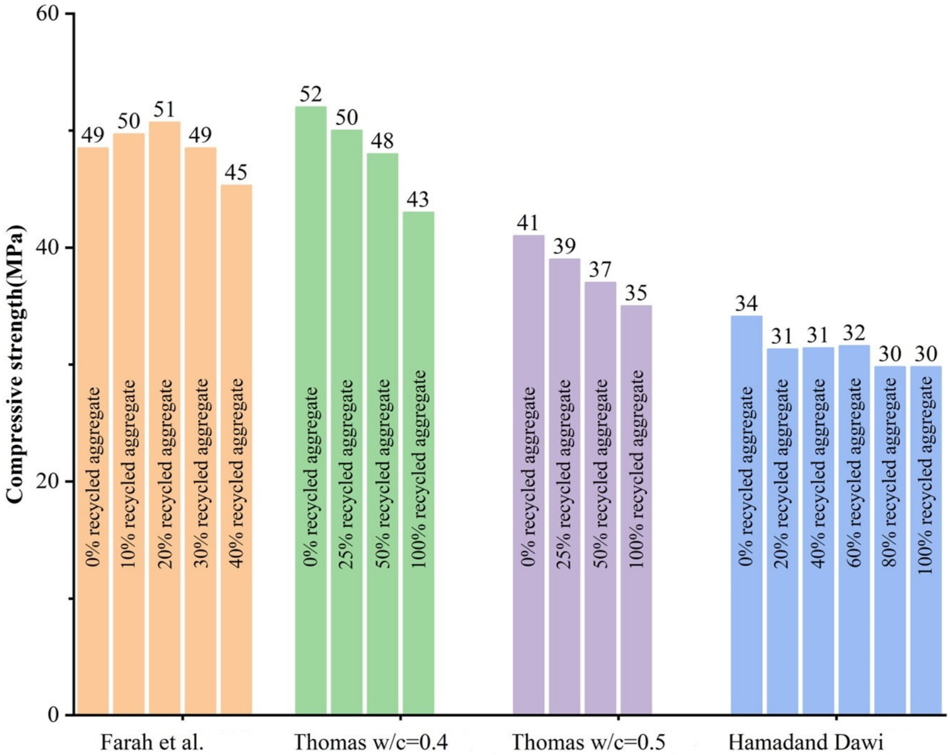

Figure 7. Trends observed in the compressive strength by various researchers with different replacement ratios of recycled aggregate. (Data from Farah et al. [65], Thomas [116] and Hamadand et al. [117]).

3.5. Flexural Strength

The evaluation of the flexural strength in concrete with recycled aggregates extends our understanding of the material's ability to withstand bending and tension forces. The concrete bending strength test is usually performed using universal press equipment, and the specimens can be selected as cube or cuboid. Figure 8 shows the three-point test approach.

Figure 8. Demonstration of the flexural strength test.

Several studies have conducted comprehensive flexural strength tests on concrete specimens with varying proportions of recycled aggregates, revealing trends similar to those observed in compressive strength studies; the flexural strength decreased with an increase in the replacement ratio of recycled coarse or fine aggregates. For instance, Rao et al. [62] investigated the flexural strength of recycled concrete with recycled coarse aggregate. The results showed that the flexural strength generally decreases as the proportion of recycled aggregate increases. When the replacement content is 25%, the flexural strength reduces to 20% compared to the normal concrete. Additionally, Topçu and Sengel. [121] prepared two series mixtures with different strength levels, that is C16 and C20. The results showed that the flexural strength of recycled concrete prepared at different strength levels decreases with an increase in the recycled aggregate content. Zhao et al. [122] conducted flexural strength tests on concrete with the incorporation of recycled fine aggregate; the results showed that the flexural strength decreased to 29.6% under the replacement ratio of 100%. Bogas et al. [67] investigated the flexural strength of normal and high-strength concrete with the incorporation of recycled aggregate. The result showed that the flexural strength of normal concrete reduced to 34% and that of high-strength concrete decreased to 36% under a replacement ratio of 100%. It is obvious that both the recycled coarse aggregate and fine aggregate cause the flexural strength of concrete to decrease; in particular, when the recycled aggregate content is high, the flexural strength decrease is more obvious. Figure 9 presents some results from numerous researchers.

On the other hand, Jia et al. [4] optimized the concrete design and used recycled aggregates instead of lightweight aggregates in lightweight concrete. The results showed that the flexural strength of the lightweight concrete increased with the increase in the recycled aggregate content. This is because the density and strength of recycled aggregates are greater than lightweight aggregates, thereby enhancing the mechanical properties of lightweight concrete. Amjad et al. [123] explored the potential benefits of incorporating Lysinibacillus boronitolerans into biomimetic self-healing concrete made with a fine brick aggregate. The results revealed that the concrete with spores immobilized in the aggregates showed a significant improvement in flexural strength compared to the control mix; specifically, the flexural strength of the concrete made with recycled fine and coarse brick aggregate increased by 22% and 15.5%, respectively. This can be explained by the densification and increased ductility of the matrix due to bio-mineralization [124,125].

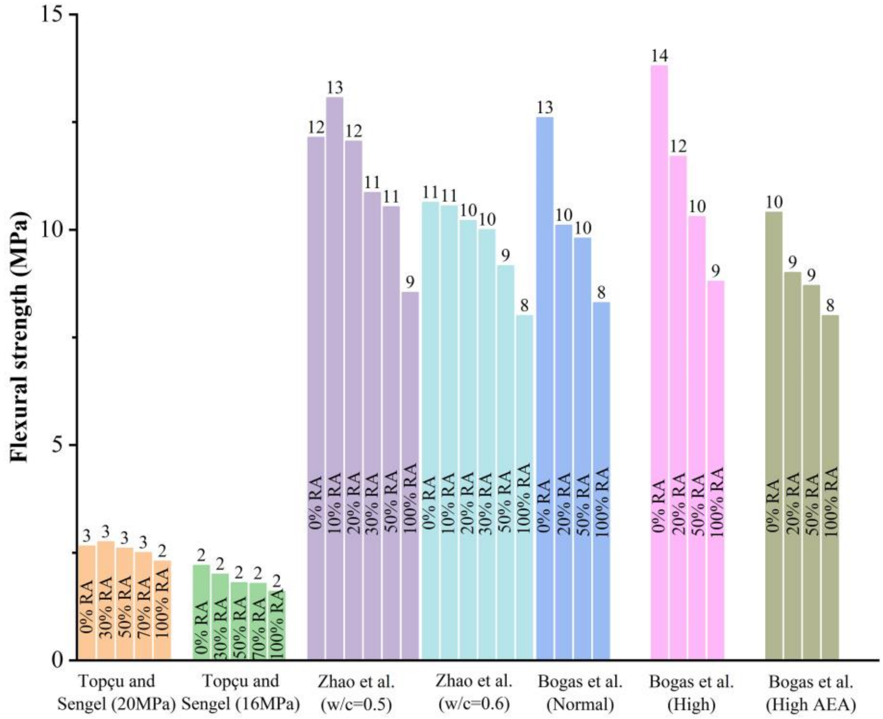

Figure 9. Trends observed in the flexural strength by various researchers with different replacement ratios of recycled aggregate. (Data from Bogas et al. [63], Topçu and Sengel [116] and Zhao et al. [117]).

3.6. Durability

Concrete durability is a key aspect in assessing structural quality and reliability, including the ability of concrete to maintain structural integrity and performance stability under a variety of external factors. There are many factors that affect the durability of concrete, such as chlorides and acids, resistance to carbonation, resistance to freeze–thaw cycles and permeability resistance to water and harmful elements, etc. [57,126,127]. The evaluation method involves non-destructive testing techniques (such as ultrasonic and rebound hammer testing) and the direct examination of samples with material properties [128,129]. In this work, the effects of chloride ions, carbon dioxide and frost damage on the durability of concrete are mainly presented. In general, the non-steady-state accelerated chloride penetration test method is one of the methods used to quickly test the resistance of concrete to chloride ion penetration (see Figure 10).

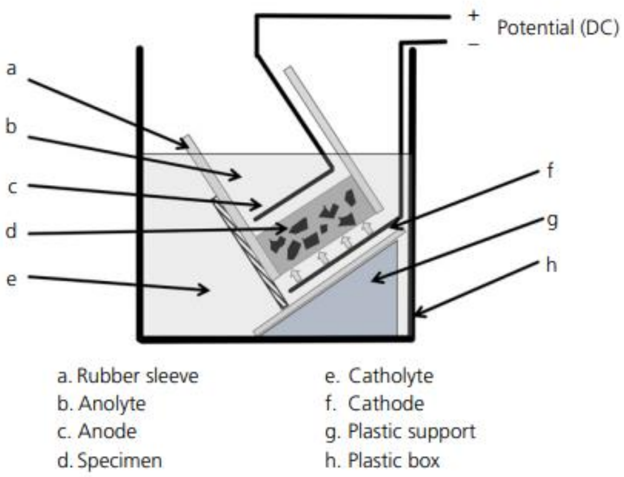

Figure 10. Schematic diagram of the non-steady-state accelerated chloride penetration test (Jia et al. [130]).

Chloride ion penetration is a durability issue that leads to the deterioration of concrete structures [130]. This process is initiated by chloride ions permeating through the connection pores of concrete and penetrating its interior. Once chloride ions react with the cementitious matrix in concrete, forming chlorides, this can result in the dissolution of minerals within the cement matrix, consequently compromising the structural integrity of concrete. Additionally, chloride ions can induce the corrosion of the reinforcing steel within concrete, leading to the formation of iron oxide and causing the expansion of the steel, ultimately creating cracks and damage in the concrete structure [131–134]. Yu and Lin [135] created a model to predict chloride diffusion in recycled aggregate concrete. The results showed that the resistance of concrete to chloride penetration decreased as the recycled aggregate content increased. Bao et al. [132] noted that with the content of recycled coarse aggregates increasing, the chloride penetration depth increases, due to the addition of recycled coarse aggregates remarkably increasing the total porosity of concrete. Zhu et al. [136] studied the chloride ion diffusion in recycled aggregate concrete under a complex environment. The results showed that the chloride ion diffusion coefficient increases with the number of freeze–thaw cycles. Additionally, Sasanipour et al. [133] studied a pretreated recycled coarse aggregate using a modification method in which the aggregate absorbed silica fume through a mixture of 1 L of water, 0.25 kg of silica fume, and 8 kg of recycled coarse aggregate. The results showed that pretreated recycled coarse aggregates improve the resistance of concrete to chloride ion penetration. Liang et al. [126] treated the recycled coarse aggregate through the absorption of calcium hydroxide and carbonization. As the recycled aggregate content or curing time increases, the ability of concrete to resist chloride ion penetration increases. This can be explained by the fact that, after the recycled aggregate is treated, the porosity decreases. Furthermore, the porosity of recycled concrete decreases and the performance of the concrete regarding chloride ion penetration is improved.

Carbonation is a chemical process that can affect the durability of concrete structures, particularly in environments where carbon dioxide is present. Concrete is an alkaline material, wherein the cement contains alkaline compounds. Carbon dioxide reacts with the alkaline substances in concrete, forming carbonate. This reaction leads to the neutralization of the alkaline substances in the concrete, reducing the alkaline environment and consequently diminishing the protective layer around the reinforcing steel within the concrete. The carbonation depth test is an important way to evaluate the resistance of concrete to carbonation. Sagoe-Crentsil et al. [137] reported a 10% increase in the carbonation depth of recycled concrete when recycled aggregate was used, as well as a parabolic relationship between the carbonation depth and square root of the exposure time that applies to recycled concrete and normal concrete. Bosque et al. [138] studied the carbonation depth of concrete with CDW and the results showed that the mean carbonation depth in recycled concretes is 1.07–1.2 times greater than that in normal concretes. Limbachiya et al. [139] found that the carbonation depth and rate increase with the amount of recycled coarse aggregate, while Lovato et al. [140] observed a proportional increase in the carbonation depth with the quantities of both recycled coarse and fine aggregates. However, Tang et al. [141] studied the reuse of aggregate carbonation and concrete carbonation in pervious concrete. The results revealed that this can improve the compressive strength while ensuring the acceptable permeability of pervious concrete, and that concrete carbonation is more effective than aggregate carbonation. The above research results show that with the addition of recycled aggregates, the resistance of concrete to carbonation weakens, which is directly related to the quality of recycled aggregates. Finally, it is recommended that the type and proportion of recycled aggregates and the addition of auxiliary materials are considered to improve the resistance of concrete structures to carbonation.

Table 6 summarizes the main information about the various works presented earlier, listing the type of recycled aggregate used, the properties studied for the developed concretes, and the main conclusions reached.

Table 6. Summary of the incorporation of recycled aggregates in concrete studies.

Study	Type of Recycled Aggregate	Properties	Main Achievements
Bogas et al. [58]	Recycled coarse lightweight concrete aggregates (RCLA)	Compressive and tensile strength, modulus of elasticity and abrasion resistance.	The RCLA improved the mechanical properties of lightweight concrete. The compressive strength increased by up to 14%, and splitting tensile strength increased by up to 32%. This is due to the cement slurry on the RCLA surface increasing its strength.
Kou et al. [59]	Low grade construction and demolition waste	Compressive and splitting tensile strength, E values, resistance to chloride-ion penetration and ultrasonic pulse velocity.	The results showed that the mechanical properties and durability of the concrete decreased with an increase in the recycled aggregate content. This is also due to the porosity and weak strength of the recycled aggregate itself. Moreover, the results demonstrated that low-grade recycled aggregates can be used to produce non-structural concrete.
Bendimerad et al. [60]	Recycled coarse and fine concrete aggregates	Plastic shrinkage and cracking sensitivity	The rate of substitution of recycled coarse aggregate had a relatively low influence on plastic shrinkage, but the concrete with 30% recycled fine aggregate showed the highest plastic shrinkage because the recycled fine aggregates develop a significant surface area. The cracking sensitivity is not proportional to the recycled aggregate content due to the fast increase in the elastic modulus and early deformation, respectively, which implied higher cracking sensitivity.
Rao et al. [62]	Recycled coarse concrete aggregates	Density, water absorption, volume of voids, compressive and tensile strength, ultrasonic pulse velocity and chloride penetration	The results showed that the volume of voids and the water absorption of the recycled aggregate concrete increased by 2.61 and 1.82% compared to the normal concrete due to the high absorption capacity of recycled aggregates. The mechanical properties and durability decreased with an increase in the recycled aggregate content due to the many transition zones and porous nature of recycled aggregates.

Table 6. *Cont.*

Study	Type of Recycled Aggregate	Properties	Main Achievements
Evangelista and Brito. [64]	Recycled fine concrete aggregates (RFCAs)	Water absorption by immersion and capillarity, chloride penetration and carbonation resistance.	The results showed that the water absorption achieved by the immersion of concrete with 100 RFCAs increased by 46%. Furthermore, the mechanical and durability decreased when the rate of replacement with RFCAs increased.
Liang et al. [126]	Recycled concrete aggregates	Physical and mechanical properties, carbonation resistance, microstructure of concrete.	This work reviewed the treatment of recycled aggregates through carbon dioxide technology, which can enhance the physical properties of recycled aggregates. Furthermore, the recycled aggregate treated use in concrete can improve the physical and mechanical properties of concrete. And in the process, carbon dioxide is also utilized as a resource.
Basha et al. [39]	Recycled plastic aggregate	Physical and mechanical properties, thermal performance of concrete	This work introduces the use of plastic waste as an aggregate for lightweight concrete. With the increase in plastic waste, the density, mechanical properties and thermal conductivity of concrete decrease.
Li et al. [120]	Waste EPS	Physical and mechanical properties of concrete	In this work, the strength of EPS waste aggregate was increased by coating the surface of EPS with epoxy resin, and the strengthened EPS aggregate was further used in concrete. The density, flow rate and strength of the concrete decreased with an increase in the EPS aggregate content.

3.7. Frost Resistance

Frost resistance is used as a durability indicator, especially in colder areas. It is mainly obtained by concrete in relation to freeze–thaw cycles (FTCs). Some researchers have verified that the frost resistance of recycled aggregate concrete is worse than that of natural aggregate concrete [142–144] and investigated how RAC is worn down during FTCs, emphasizing the potential deterioration mechanism. The key factors affecting the frost resistance of recycled concrete have also been investigated, including the type of recycled aggregate, the properties of the parent concrete, the rate of replacement with recycled concrete, the moisture state of the recycled concrete and the coupling effect between recycled concrete and other factors [145–147]. Sun et al. [148] found that the frost resistance of RAC with only RFA replacement was significantly lower than that of NAC. The main reason for this is that RFA has a higher porosity, resulting in heightened water absorption and saturation in RAC during FTCs, and the aggravation of surface spalling. Ajdukiewicz et al. [149] examined the frost resistance of high-strength RAC made from a high-strength parent concrete (63.2–72.3 MPa). Their results showed that the frost resistance of RAC was comparable to or even slightly higher than that of NAC. Furthermore, scholars have been constantly looking for effective methods to improve the frost resistance of RAC, but also to optimize the prediction of frost resistance, such as models for predicting the durability evolution of RAC in the freeze–thaw environment. Zhi et al. [150] proposed a probabilistic damage model based on a two-parameter Weibull distribution to establish the relationship between the freezing–thawing cycles and key parameters: the RFA replacement ratio, water-to-cement ratio, and water absorption of RFA. In this research, they clearly demonstrate that the result of this model's prediction is basically consistent with the result of the experiment: the frost resistance of RFA concrete decreases significantly with the RFA replacement ratio and the other factors above. Zhi et al. [151] also established RAC models based on the method of RBSM, and adopted it to research more examples of RAC, obtaining a comprehensive view of the frost resistance of RAC with different factors: air entrainment, the water-to-cement ratio and replacement ratio. The frost resistance is an important factor associated with the durability of RC that needs further optimization in future work.

3.8. Further Studies

In summary, the research on the future of recycled aggregates can be further explored in the following aspects: the source of recycled aggregates, the refined classification of CDW and research on practical engineering applications, research on the durability of recycled aggregates, and the study of solutions to improve the durability of recycled aggregates; this is in order to promote the sustainable management and utilization of construction and demolition waste and achieve the goal of resource recycling and environmental protection.

4. Conclusions

This study comprehensively investigated the incorporation of recycled coarse and fine aggregates in concrete, focusing on the physical, mechanical, and durability properties of sustainable concrete. The key findings and implications drawn from this research are summarized below:

The type of building and CDW recycling process plays a key role in the physical properties of recycled aggregate. The analysis of recycled aggregates revealed a diverse range of sources and compositions, influencing the physical and mechanical properties of concrete. Recycled aggregates can be produced with different particle sizes as required.

The workability of fresh concrete was found to be influenced by the percentage of recycled coarse or fine aggregates, with higher substitution rates leading to reduced workability. In general, the superplasticizer was used to optimize the workability of fresh concrete. The higher porosity and lower density of recycled coarse and fine aggregates led to the concrete having a higher water absorption and lower density. It is therefore crucial to optimize concrete design to obtain high-quality concrete.

The compressive strength and flexural strength were assessed to understand the structural performance of concrete containing recycled aggregates. This study revealed a nonlinear relationship between the substitution rates and compressive strength, emphasizing the need for careful optimization. Additionally, the incorporation of fibers showed promise in enhancing the flexural strength of recycled aggregate concrete.

The resistance of concrete made with recycled aggregates to chloride ion penetration and carbonation was reviewed. Most studies showed that with the incorporation of recycled aggregate, the resistance of concrete to chloride ion penetration and carbonation decreased. This behavior was justified by the higher porosity of recycled aggregate. Therefore, improving the durability of recycled concrete is important in improving the widespread application of concrete.

The research highlighted the need for further experimental explorations addressing the replacement of natural aggregates with both coarse and fine recycled aggregates. Future studies should delve into optimizing mix designs, exploring alternative reinforcement strategies, and investigating the long-term performance of structures incorporating recycled aggregates under diverse environmental conditions.

In conclusion, this study contributes valuable insights into the comprehensive application of recycled coarse and fine aggregates in concrete. The findings presented here provide a foundation for informed decision-making in sustainable construction practices, emphasizing the importance of balancing environmental goals with structural performance considerations. Continued research in this field is essential for advancing the practical implementation of recycled aggregates in the construction industry. Continuous research in this field is imperative to propel the practical utilization of recycled aggregates in the construction sector. Moreover, by elucidating the influence of recycled aggregates on the physical and mechanical properties and durability of concrete, there arises a need for forthcoming investigations into the performance of recycled aggregates in concrete applications to enhance specific aspects of concrete performance.

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