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Review

A Comprehensive Review on Recycling of Construction Demolition Waste in Concrete

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Abstract: There have been efforts to use building demolition waste as an alternative aggregate in concrete to decrease the use of natural resources for construction. The World Green Building Council estimates that the construction industry is responsible for more than 50% of all material extracted globally and that construction and demolition waste makes up 35% of global landfills. As a result, incorporating recycled aggregate (RA) in concrete production is a prudent course of action to reduce the environmental impact. This study reviews prior research on using recycled aggregate instead of conventional ingredients in concrete. The composition and morphology of different types of RA, the behavior of RA in fresh and hardened states, keyword co-occurrence and evolution analysis, and the various additives used to enhance the inferior properties of RA are discussed. The RA showed different physical properties when compared with natural aggregate. However, the addition of pozzolanic materials and various pretreatment techniques is desirable for improving the inferior properties of RA. While building waste has been utilized as a substitute for fine and coarse aggregate, prior research has demonstrated that a modified mixing approach, an adequate mixing proportion, and the optimum replacement of cementitious materials are necessary. Based on the review, the recommendation is to use RA at a replacement level of up to 30% and the addition of precoated and pozzolanic materials as a treatment to provide concrete with adequate workability, strength, and durability for structural applications.

Keywords: cementitious materials; construction and demolition waste; fresh and hardened properties; recycled aggregate; sustainability

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1. Introduction

Construction and demolition waste materials are accumulated during the construction, modernizing, rehabilitation, retrofitting, or demolition of infrastructures. Almost one million tons of construction and demolition waste (CDW) materials are created annually using natural resources, mainly for construction purposes. It is high time to pay earnest attention to the damage done by CDW. Most countries lack processing facilities for these CDW materials, so waste materials are dumped rather than utilized and recycled in the construction of new buildings [1]. We have observed a rapid increase in the use of CDW materials in order to make sustainable concrete with the environment and people's lives in mind. However, further analysis indicates that the use of waste materials in concrete significantly affects its mechanical performance [2]. Compared with conventional aggregates, recycled aggregate (RA) materials show a reduction in specific gravity, an increase in porosity, the crushing index, and water absorption, and a weak interfacial transition zone. Generally, the root cause of the problems with RA mentioned above is that aggregates are produced from crushed and discarded concrete blocks, making them angled, sharp, and porous on the surface [3,4]. Therefore, more work is required in order to develop the standards and to reduce the effects of the hydrated paste that sticks to the surface of crushed coarse aggregate in an economically feasible way.

Based on the research findings, the usage of RA is limited due to the lack of structural standards for RA [5]. It may be that an insignificant amount of construction waste is recycled or used as a substitute to construct the naturally sourced materials. The adaptation of CDW materials as a substitute for natural aggregate has become a circular economy priority. Globally, about 20 billion tons of natural resources are used each year to produce fresh concrete; over the next 20 to 30 years, that amount is predicted to triple. However, the demolition of existing buildings produces a significant amount of solid waste. It makes up 20 to 40% of the total waste and has been identified as one of the world's most prominent environmental contaminants [6]. This waste, which takes up usable landfill areas, also constitutes a health risk. Using RA instead of natural aggregate (NA) offers a viable answer to the problems of resource exploitation, the restoration of land spaces, and decreasing waste in landfills [7]. Moreover, RA is a natural aggregate substitute that supports sustainable construction.

However, the complete substitution of NA with RA causes the strength characteristics of the concrete to deteriorate. Although RA substitution has been found to deteriorate the mechanical characteristics of concrete, it has been claimed that recycled concrete aggregate (RCA) is unaffected by the compressive strength of recycled aggregate concrete up to the 30 percent by weight substitution level, after which it decreases [8]. The harmful effects of RA have been minimized by various methods over the past few decades. Some of the treatment techniques for the improvement of RA are NO_2-sequestered recycled concrete aggregate [9], the replacement of cement with a combination of recycled aggregate and crushed reclaimed concrete [10], the liquid–solid carbonation process [11], recycled aggregate with a crystallization agent [12], the substitution of various admixtures, such as GGBS, fly ash, bottom ash, silica fume, and nano-silica, in the cement, the combination of nano-silica and titanium oxide, precoating the recycled aggregate with a calcium hydroxide solution [13], the chemical–thermal treatment [14], and fluidity-based recycled aggregate mortar [15]. Still, cost-effective and environmentally friendly RA improvement techniques must be devised as a possible alternative in order to increase the use of RA in concrete applications.

As a result, comparative feasibility analysis is critical in focusing the research on a simple narrow path to strengthen the various properties of recycled concrete aggregate in a cost-effective and simplified manner. The enormous number of articles published annually on recycled concrete aggregate provide the experimental analysis for structural applications. From 1995 onwards, the amount of research on waste concrete and the number of publications increased yearly. Until 2004, less than 10 articles relevant to recycled aggregate were published each year. The increasing interest in RCA research and the number of publications are shown in Figure 1. In 2020, the number of articles published was the highest (293). The research in 2020 mainly focused on water absorption and chloride penetration [16], rice husk ash substitution [17], fly ash and ground granulated blast furnace slag (GGBS) [18], and the addition of blended pozzolanic materials [19]. In 2021, until the 10 September, 242 articles had been published. These are focused on concrete with RCA [20], the bond behavior of RCA with basalt-fiber-reinforced polymer bars [21], and transport properties [22]. This trend appears promising and indicates that RCA research has been active for more than five decades. Due to the scale-up of the circular economy, researchers have focused mainly on recycled aggregate materials, and it has been proven that the growth of published articles has tended to increase exponentially.

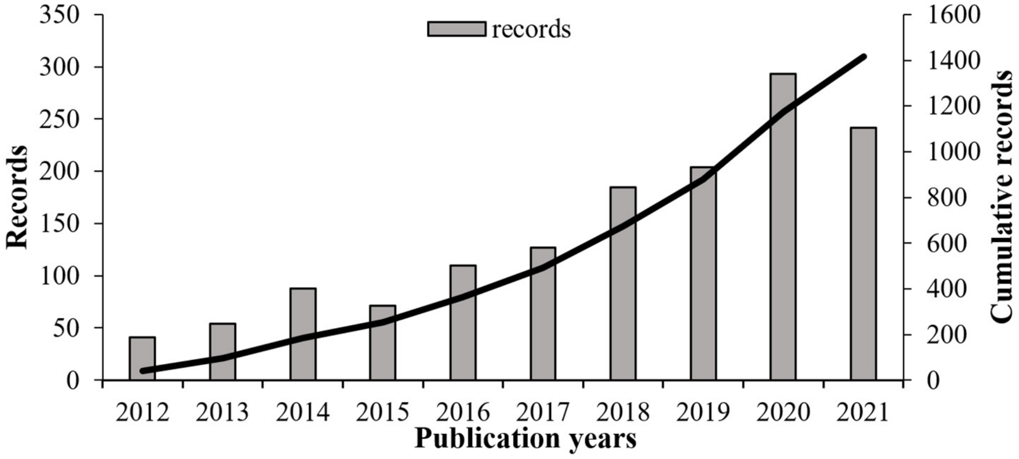

Figure 1. The number of published articles for the period 2012–2021.

The annual generation of CDW in some countries, such as China [23], the United States [24], India [25], Australia [26], England [27], the European Union [28], France [29], and Italy [30], is shown in Figure 2. The recycling rate is higher in the United States; of the 600 MT of building and demolition waste, around 75% is recycled. In China, it has been stated that less than 40% of the CDW is recycled [23]. In addition, just 1% of India's CDW is recovered and recycled. In order to safeguard the environment and to reduce natural material exhaustion, appropriate handling techniques for CDW are necessary.

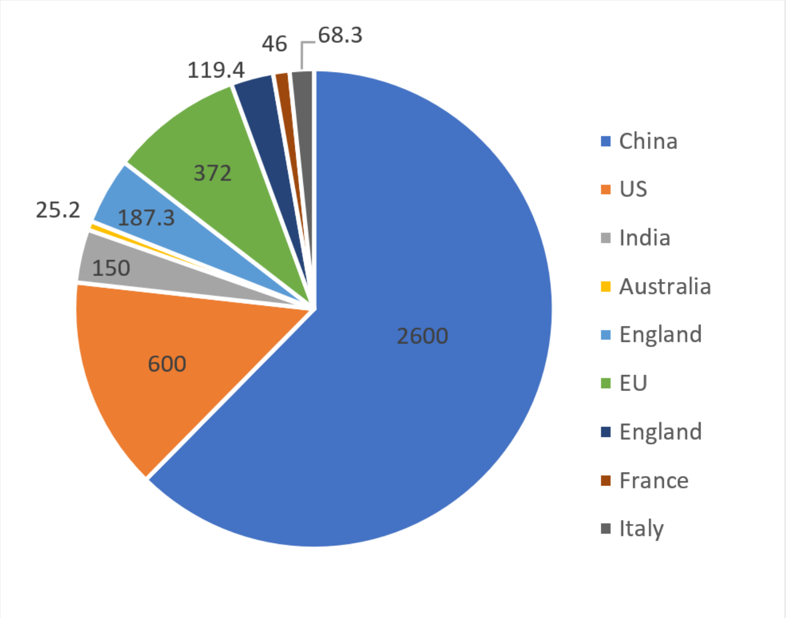

Figure 2. Annual Generation of CDW in Million Tons.

Significance of the Review

This literature review provides valuable information regarding the utilization of RA in concrete applications. This comparative review on RA aims to provide crystal-clear information about the variation in physical and chemical properties of different types of recycled aggregates. Additionally, this study explains the quantitative information about how the treatment methods improve the inferior properties of recycled aggregates, the fresh and mechanical properties of concrete, and durability aspects for fine and coarse aggregate substitution. Furthermore, a scientometric review on recycled aggregate concrete between 2012 and 2021 provides valuable information about the most minor and most studied areas, which may act as a roadmap for research on recycled aggregate concrete.

2. Literature Review on Recycled Aggregate

2.1. Composition of Recycled Aggregate

Recycled aggregate (RA) has different categories, including recycled concrete aggregate (RCA), fine recycled concrete aggregate (FRCA), recycled ceramic aggregate, recycled masonry aggregate (RMA), coarse mixed recycled aggregate (CMRA), and fine mixed recycled aggregate (FMRA). RA is mainly composed of SiO_2, CaO, and minor oxides. The quantities of the different chemical compositions identified by various authors are shown in Table 1 and are comparable with natural aggregate's composition. Calcite is a prominent mineral in recycled aggregate, but "quartz, alkali feldspars, muscovite, and dolomite" have also been recognized [31]. Similar results show the presence of crystalline phases such as quartz and calcite in RA samples compared with natural aggregate [32]. The presence of crystalline phases is consistent with the finding of quartz and calcite in the recycled aggregate's X-ray Diffraction (XRD) pattern, as shown in Figure 3. In fine natural aggregate, the resulting peak position in the XRD pattern revealed the existence of the crystalline compound SiO_2. The occurrence of SiO_2 might be a helpful circumstance for developing a calcium hydrate gel that enhances the concrete's strength. Two significant peaks of SiO_2 and $CaCO_3$ can be seen in the fine recycled aggregate's XRD pattern. The feasibility of substituting RA as an appropriate alternative for NA has been indicated due to the presence of the crystalline component SiO_2. Additionally, the peak of $CaCO_3$ can be seen because of the old hardened paste's adhesion to the surface of the FRA [33].

Table 1. Major components of recycled aggregate from the literature.

Literature	Aggregate Type	Country	SiO_2 (%)	CaO (%)	Al_2O_3 (%)
Nedeljkovi et al. [34]	FRCA	Netherland	66.4	21.5	5.0
Alexandridou et al. [31]	FMRA	Northern Greece	34.3	27.52	6.4
	CMRA		18.4	39.5	3.6
	FMRA	Southern Greece	10.9	45.2	2.03
	CMRA		8.3	47.6	1.7
Moreno-Pérez et al. [35]	FMRA	Canada	51.5	19.6	13.7
	CMRA		51.1	23.3	13.2
Angulo et al. [36]	FMRA	Brazil	73.9	5.45	7.0
	CMRA		67.1	7.8	9.8
Kirthika et al. [37]	FMRA	India	68.9	4.5	11.5
Silva et al. [32]	CMRA	Brazil	52.4	15.6	11.6
Sivamani et al. [33]	FMRA	India	71.2	14.13	5.51

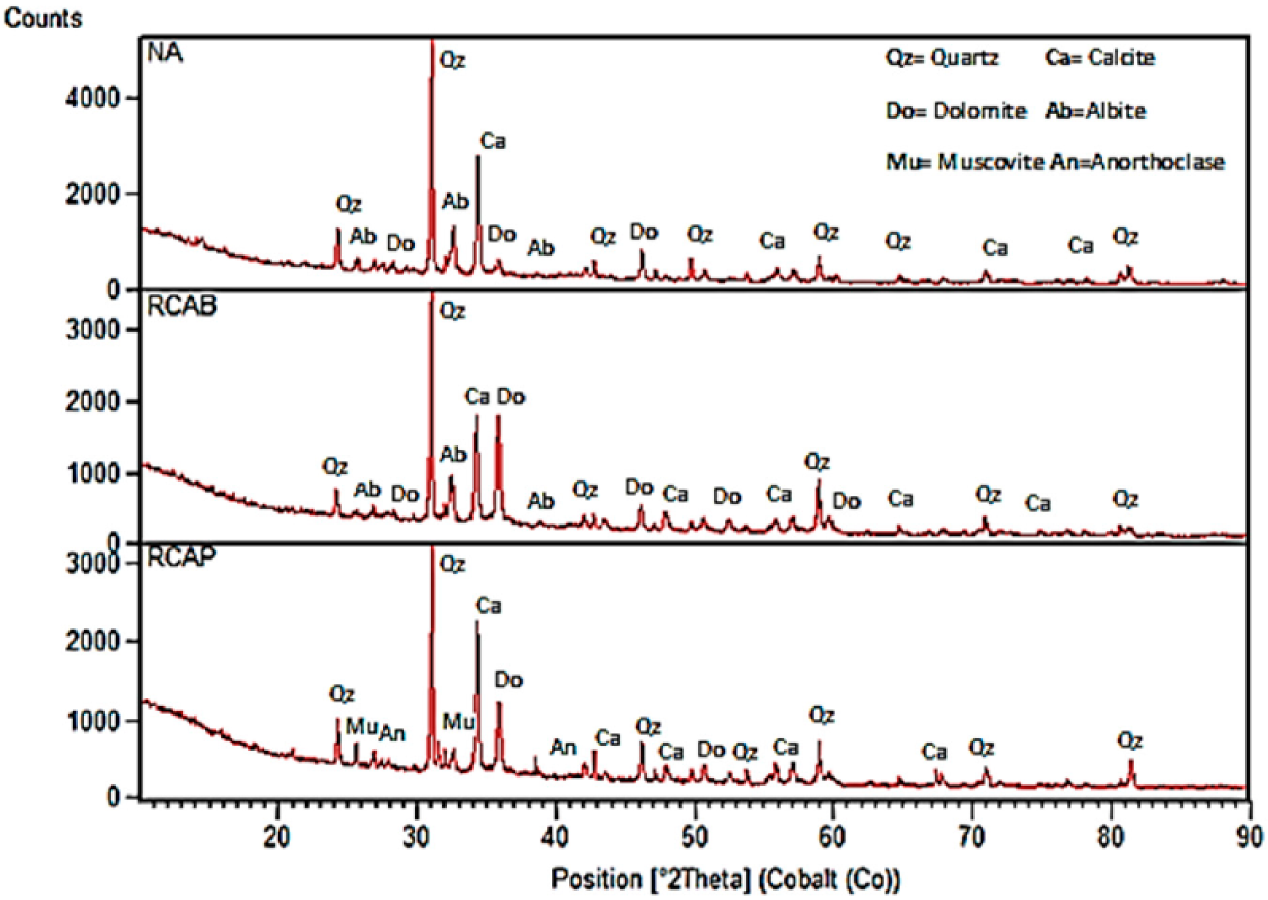

Figure 3. XRD pattern of NA and RA from pavement and building waste [38].

Secondary electron images from scanning electron microscopy of the NA and RA are shown in Figure 4 and can be used to confirm the morphology and interfacial zone of the recycled aggregate. It is feasible to distinguish between the RA and NA in the images produced by scanning electron microscopy. Aggregates made from recycled materials are less durable than aggregates made from natural materials. Recycled aggregates have a diverse, erratic, and inconsistent microstructure. Recycled crushed concrete is coated mainly with fine fractions and old cement mortar [39]. The coarse recycled aggregate has a rough surface with sharp edges, and a portion of the outer layer is bound with old mortar with cracks and surface defects. The scanning electron microscopy images show the angularity in both manufactured sand and FRA particles. Both aggregates show that the increased number of angular parts is due to the crushing process during the production of RA from CDW. In addition, the presence of hardened cement paste on the outer part of the RA is evidenced.

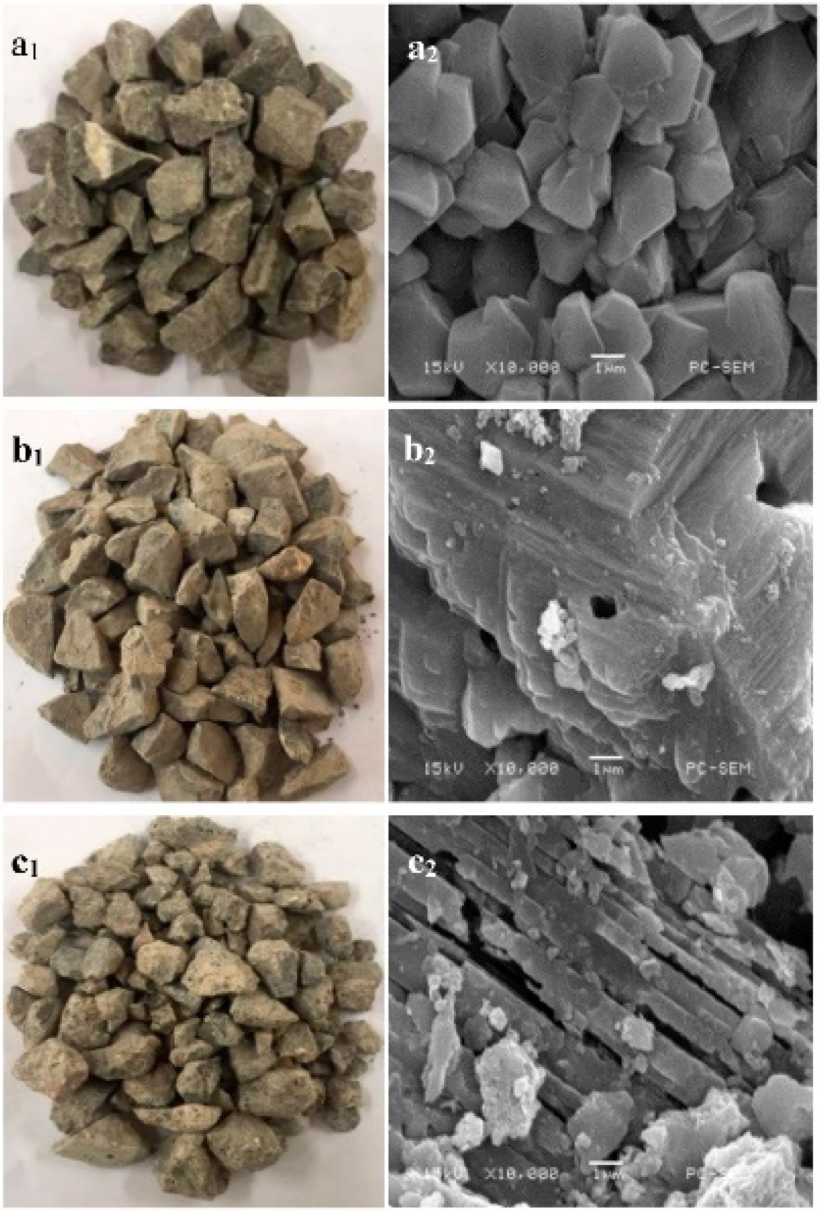

Figure 4. SEM images of NA and RA in subsequent recycling cycles. (**a1**) NCA, (**a2**) SEM image, (**b1**) RCA1, (**b2**) SEM image of RCA1, (**c1**) RCA2, (**c2**) SEM image of RCA2 [40].

2.2. Treatment of Recycled Aggregate

Here, we discuss the change in the aggregate's attributes after it is used in concrete, various ways different authors have improved the destructive properties, and the extent to which the properties improved. The physical properties of untreated recycled aggregate are shown in Table 2. Additionally, the enhancement of the physical properties due to various treatments is shown in Table 3. Although the recycled aggregate from lower-grade concrete had a more porous structure, adding more cement paste to the carbonation treatment was beneficial. The carbonation treatment can effectively increase the mortar's adhesion to aggregates if the aggregate surface area is increased. The carbonation treatment produced a reduction in the water absorption and crushing values of 22.6–28.3% and 7.6–9.6%, respectively. The workability of the concrete was improved when recycled particles absorbed less water [41]. The properties of the supplementary cementitious materials (SCMs) added to the recycled aggregate concrete improved when the two-stage mixing approach (TSMA) was used. The recycled aggregate had a water absorption rate of 6.1% at first. Then, the SCM was added to the recycled concrete and it reduced the water absorption rate by 2–8%. The TSMA technique also effectively reduced the water absorption rate [42]. A previous study revealed that the water absorption rate of 0.81% in natural aggregate (NA) increased to 5.32% in recycled concrete aggregate (RCA). After a hydrochloric acid immersion treatment, the water absorption rate was reduced by 17.11% in the RCA. Impregnation with calcium meta-silicate (CM) reduced the water absorption rate by 18.08%. In addition, the aggregate impact value increased from 14% to 23% in the recycled coarse aggregate. The acid and CM treatments reduced the crushing value to 13.05% and 17.4%, respectively, in the treated aggregates [43].

Table 2. Physical properties of recycled aggregate.

Literature	Size (mm)	Aggregate Type	Unit Weight (kg/m^3)	Specific Gravity	Water Absorption (%)	Crushing Value (%)	Flakiness Index (%)
Hamada et al. [44]	4.75–25.4	RCA	1389	2.29	5.1	-	-
	4.75–12.7	RCA	1376	2.35	4.8	-	-
Yu et al. [37]	4–16	RCA	1230		3.21	21.26	-
Kumar et al. [45]	<4.75	FMRA	1290	2·08	11·91	-	-
Cantero et al. [46]	12–22	MRA	-	-	5.27	-	10
	6–12	MRA	-	-	6.28	-	10
Yan et al. [32]	5–26.5	MRA	1169	-	3.02	15.6	-
	5–26.5	RMA	877	-	11.14	28.8	-
Meng et al. [32]	9.75–31.5	MRA	-	-	8.8	18	-
	0–9.5	FMRA	-	-	13.2	22	-
Sim et al. [47]	5–25	RCA	-	2.55	1.68	-	-
	0.15–5	FRCA	-	2.28	6.45	-	-
Guo et al. [48]	5–31.5	RCA	1405	-	3.8	-	-
	0.15–5	FRCA	1482	-	5.5	-	-
Raman et al. [49]	4.75–20	RCA	1480	2.41	3.52	38.39	
Babalola et al. [50]	4.75–25	RCA	1490	2.35	5.2	-	-
Saleem Kazmi et al. [33]	4.75–20	RCA	1414	2.55	6.85	31	-
Mahmood et al. [51]	20–15 (40%) 15–5 (60%)	RCA	-	2.43	4.5	47.82	-

Table 3. Improvements in the physical properties of recycled aggregate.

Literature	Aggregate Type	Treatment Methods	Before Treatment	After Treatment	Effects on Enhancement
			WA (%), Density (ρ) (kg/m^3)		
Zhan et al. [52]	RCA	Carbonation (Optimum treatment duration, 7 days; Pressure, 1 bar)	WA: 7.52	WA: 5.76	The treatment induced the carbonation of portlandite, resulting in an increase in calcium carbonates that filled the pore gaps and increased the density of the microstructure.
			ρ: 2636	ρ: 2700	
Zeng et al. [53]	MRA	Soaking in a nano-silica suspension of 15% nano-silica particles by weight. (Optimum, 1 h of soaking)	WA: 8.22	WA: 7.38	The surface of the recycled aggregate would be penetrated and altered by nano-silica particles, increasing the density of the concrete microstructure.
			ρ: 2566	ρ: 2588	

Table 3. *Cont.*

Literature	**Aggregate Type**	**Treatment Methods**	**Before Treatment**	**After Treatment**	**Effects on Enhancement**
			WA (%), Density (ρ) (kg/m^3)		
Al-Waked et al. [54]	MRA	Accelerated carbonation (5 days of carbonation treatment, 50% CO_2 concentration)	WA: 6.1	WA: 3.3	This enhancement occurs due to the transformation of portlandite to calcite and the development of amorphous carbonation products.
		Pretreatment using sodium silicate–silica fume solution (Optimum replacement level, 5%; soaking time, 4 h)	WA: 6.1	WA: 4.1	Immersion in a pozzolanic solution fills the pores of the RA and forms a C-S-H gel by mixing with CH crystals that fill the gaps in the recycled aggregate.
Al-Bayati et al. [55]	RCA	Heat treatment (Optimum heating, 350 °C)	WA: 5.91	WA: 5.35	High temperatures between 400 and 600 °C make the aggregate experience internal stress due to thermal expansion.
		Soaking in HCl (0.1 M for 24 h)	WA: 5.91	WA: 5.66	A strong acid does not reduce the impact of acid attacks as effectively as a mild acid.
		CRCA soaking in acetic acid (0.1 M for 24 h)	WA: 5.91	WA: 5.79	
Wang et al. [12]	RCA	Treatment with a water-based liquid crystallizing agent (Optimum immersion, 7 d; aggregate/solution ratio, 2 kg/L)	WA: 7.13	WA: 2.96	When a crystallizing agent was added, C-S-H formed and minimized the porosity of the recycled concrete aggregate
Damrongwiriyanupap et al. [56]	RCA	Coating with cement paste	WA: 7.54	WA: 3.25	The development of calcium silicate hydrate can fill the gaps in the RCA.
		Coating with a high-calcium fly ash paste that has been alkali-activated (10 M NaOH and Na_2SiO_3)	WA: 7.54	WA: 2.10	Unreacted cement grains in the RCA might react with water, fly ash, dolomite, SiO_2, and Al_2O_3 to create hydration products at the interfacial transition zone.
		Alkali activation of fly ash paste regulated by a dolomite coating (10 M NaOH and Na_2SiO_3. The dolomite was oven dried at 100 °C)	WA: 7.54	WA: 2.55	

The carbonation treatment and the addition of pozzolanic slurry (nano-SiO_2, silica fume, and fly ash slurry) reduced the water absorption rate by 21–26% and increased the density of the RCA [57]. The combination of a superfine powder (fly ash, phosphorous slag, and GGBS) and a superplasticizer was found to correct the defects and fill the space between the cement particles in RCA [58]. An acid, such as H_2SO_4, works more efficiently than hydrochloric acid (HCl) at a concentration of 0.1 moles. The maximum achieved reduction in the water absorption rate of RCA was 0.92 for HCl, 0.81 for H_2SO_4, 0.93 for scrubbing and heating, and 0.78% for scrubbing compared with 1.56% for untreated RCA. In the heating–scrubbing mechanism, concrete debris was heated in an oven to over 300 °C for up to 24 h and then allowed to cool, making the cement paste brittle. Subsequently, mechanical rubbing was performed in a Los Angeles abrasion machine for a few minutes to achieve a more significant reduction in the water absorption rate, which was about 0.78% compared with the untreated RCA (1.56%). Nevertheless, the water absorption rate of the treated RA was still higher than that of NA [59].

The immersion of RCA in a crystallization agent was carried out with 2 kg of aggregate in a 1 l solution at around 25 °C. After a one-day immersion period, the RCA's absorption nature had been lowered by 24.82%. After a seven-day immersion period, it was further reduced by 58.49% compared with the untreated RCA's absorption rate (7.13%). The one-day and seven-day period of immersion in a crystallization agent reduced the relative surface roughness from 106.8% (natural aggregate) to 100.2% and 93.6%, respectively [12]. The water absorption (WA) of the treated RCA at an acetic acid concentration of 1% during a one-day immersion period was reduced by 16.97% compared with untreated RCA. The WA of RCA was optimally lowered with a concentration of acetic acid of 1% and a one-day immersion period. The aggregate's characteristics (specific gravity, density, and WA) were primarily selected to produce the ideal concrete mix [60]. These characteristics were improved by adopting various treatment methods or production processes to utilize RCA at a higher replacement percentage in ordinary concrete.

The adhered mortar in RCA is a significant problem as the greater porosity leads to an increase in the WA. The surface treatment method may reduce or strengthen the loose mortar particles, improving the qualities of recycled aggregates considerably. The properties of RCA are determined by the elongation index, the crushing value, the amount of old mortar, and the grade of the old concrete. The mechanical grinding of the attached mortar off the RCA's surface within a drum mixer, together with the addition of water, can help to weaken the adhered mortar. This grinding method is comparable to the Los Angeles abrasion test but does not use steel spheres [61]. RCA's physical and mechanical properties can be enhanced by mechanical abrasion. Silica fume impregnation can reduce the permeability by filling the voids in the recycled aggregate [62]. With the help of a lime treatment, much more progress can be made. Quicklime can be mixed with water in the RCA treatment to make a lime solution. Initially, the grinding of RCA in a Los Angeles abrasion machine for a duration of 5 min, followed by treatment with a lime solution not exceeding 2 N, is recommended for the removal of the maximum amount of old or adhered mortar [63].

Other alternatives include HCl and sodium sulphate (Na_2SO_4) in a proportion between the aggregate and the solution of 1:4.5. These treatments have been proven to dislodge previously bonded mortar from RCA. Between these treatments, the HCl pretreatment is a more effective treatment method. However, to optimize the waste management system, the reusability of pretreatment solutions must be assessed [64]. For example, a mix of 15% waste concrete power (WCP) and 15% spontaneous combustion gangue powder (SCGP) provides the characteristic of impermeability due to the increased pozzolanic activity of SCGP and WCP [65].

Similarly, modification methods such as mild acetic acid treatment followed by mechanical grinding [66], the spraying of nano-silica on the mixed recycled aggregate followed by soaking in a polymer [67], bio-cement treatment [68], wastewater-enhanced flow-through carbonation [69], the addition of a cement paste dissociation agent [70], the mineral addition treatment method with silica fume, and the equivalent mortar volume method [71] have been used by various researchers to enhance the inferior properties of RCA. These methods were developed to produce recycled aggregate concrete with improved properties. It is necessary to build a cost-effective and environmentally friendly approach, as this would be a practical way to utilize recycled aggregate in concrete applications.

2.3. Fresh Concrete Properties

Since recycled aggregate has different properties compared with natural aggregate, it reacts differently in fresh concrete mixes, resulting in differences in the amount of mixing water required, the fresh density, and the concrete's workability. The variation in the workability of RA is shown in Table 4. The variation in performance between the fresh properties of RA concrete and conventional NA concrete is discussed in this section. The two-stage mixing approach reduces the workability because of the prolonged mixing period and increases the absorption of the recycled aggregates. However, TSMA together with supplemental cementitious ingredients was found to improve the RCA concrete's workability [42].

Table 4. Effect of recycled aggregate on workability.

Reference	W/C Ratio	Aggregate Type	Replacement Level (%)	SP Dosage (%) and Type of SP	With or Without Admixture	Slump Value (mm) ↑↓
Tangchirapat et al. [72]	0.48	CRCA	Up to 100	-	-	Up to 70 (+16.7%)
		FRCA + CRCA			-	Up to 50 (−16.7%)
		CRCA			FA up to 50%	Up to 100 (+42.8%)
		FRCA + CRCA			FA up to 50%	Up to 90 (+80.0%)
Kumar et al. [45]	0.42	FMRA	Up to 100	0·25 (polycarboxylate ether)	-	Up to 40 (−48.7%)
Chih Fan et al. [73]	0.35	FRCA	Up to 100	1 (type G)	-	Up to 180 (−10.0%)
	0.55				-	Up to 195 (−9.7%)
de Andrade et al. [74]	0.45	FRCA	Up to 100	0.4 (Glenium 51)	-	Up to 165 (+153.8%)
Cantero et al. [75]	0.45	MRA	Up to 100	1.55 (water-based polycarboxylate)	-	Up to 140 (+27.27%)

Consequently, as the replacement level of recycled fine aggregate (RFA) increased, the quantity of mixing water also increased. The amount of water to be mixed increased by 12.30, 23.29, and 34.29% with an RFA replacement level of 0, 50, and 100%, respectively [76]. This was because of the increased water absorption of the RFA, which was 11.91% compared with that of the fine natural aggregate (0.94%). The workability of the recycled aggregate was lower than that of the NA due to its higher water absorption rate. However, the HCl-treated RA obtained a maximum workability of 90 mm, which was greater than that of the untreated RAC concrete (65 mm) [59]. Since the carbonation decreased the water absorption of the RCA, the mortar in the carbonated RCAs had superior flowability. On the other hand, the increased addition of recycled aggregate in conventional concrete showed a reduction in the workability from 45 to 20 mm at a constant replacement level of 6.5% metakaolin. The reduction in workability occurred due to the incorporation of pozzolanic materials that disrupt its bonding networks [77].

The fluidity of the mixes decreased by around 32 and 17% after treating RCA with silica fume and nano-SiO_2 slurries. This decrease in fluidity was due to the fine coating of pozzolanic materials on the surface of the RCA, which absorbed some of the mixing water and left a smaller amount of free water in the concrete mixes. However, the silica fume grains that had adhered to the outer surface of the recycled aggregate increased the workability by preventing some of the water from permeating into the pores present in the RA, increasing the quantity of free water in the mixture. Additionally, the reduction in the workability of the concrete was around 12% and 24% at a 50% replacement level of RFA and RFA along with GGBS, respectively. Compared with conventional concrete, the 50%

RFA specimens with 70% SCM (23% fly ash and 47% GGBS) increased the workability by 40% [78]. The different behavior of the RCA in the fresh state was due to the aggregate absorbing more water and having the weakest mortar. However, with treatment methods with a proper mix design and modifications in the water-to-cement ratio, it would be feasible to make concrete with the necessary workability.

2.4. Properties of Hardened Concrete

It is crucial to understand how various proportions of recycled aggregate affect the concrete's strength properties and to predict how the concrete will behave in structural components. Table 5 reports the hardened properties of RA concrete in comparison with conventional concrete. The different treatment methods improved the hardened properties of the RA. The nano-silica-coated RA, treated at an optimum concentration of 2% for 48 h, improved the hardened properties even at a replacement level of 100% due to the increased hardness, the decreased water absorption, and the reduced number of pores present in the RA [79]. The reinforcement of the recycled aggregate concrete with the dispersion of basalt fibers improved the RA's inferior properties, strengthening the interfacial transition of the RA [80]. In addition, the replacement of construction waste can be utilized in the form of ground carbonated reactive MgO cement to produce fresh reactive MgO cement in order to increase the utilization of construction waste. The use of carbonated reactive MgO cement at a replacement level of 20% could improve the RA's detrimental properties due to the formation of amorphous hydrated phases [81]. Although RA behaves heterogeneously, the studies reveal that the mechanical properties could be enhanced even with high recycled aggregate content.

Table 5. Studies on the hardened properties of concrete.

SI. No	Literature	Replacement Level (%)	Additives	Effects on Strength Parameters
1.	Hamad et al. [44]	0, 40, and100	–	CS *: 33.4, 30.7, and 29.5 MPa STS **: 4.98, 4.56, and 4.37 MPa Modulus of elasticity: 31,602.1, 27,130.7, and 28,596.8 MPa Flexural strength: 196.8, 213.7, and 227.2 kN Shear strength: 162.9, 162.8, and 159.3 kN Bond strength: 119.2, 137.9, and 121.2 kN for 0, 40, and 100% RCA, respectively.
2.	Zhang et al. [41]	100% RCA	Carbonation treatment	Carbonated aggregate showed 15 and 10% higher CS 7 and 28 days after treatment, respectively.
3.	Faysal et al. [42]	60% RCA	SCM with a two-stage mixing approach (TSMA and SCM containing fly ash (20%), GGBS (20%), and silica fume (7%)	Silica fume containing a concrete mixture • Maximum CS: 56.3 MPa • Maximum STS: 3.1 MPa
4.	Sunayanaet al. [82]	100% RA	20 and 30% fly ash	RAC with 30% fly ash reduced: • The CS by 6%; • The STS by 28%; • The modulus of elasticity by 12%.

Table 5. *Cont.*

SI. No	Literature	Replacement Level (%)	Additives	Effects on Strength Parameters
5.	Guo et al. [83]	50 and 100% RCA	50 and 75% by weight of quaternary cementitious materials: cement, fly ash (FA), slag, and silica fume (SF)	100% recycled aggregate concrete with quaternary cementitious materials increased the CS: • At the 50% replacement level by 12.6%; • At the 75% replacement level by over 35 MPa • In the ternary mix (fly ash and slag) by 83% to 174%; • In the quaternary mixes by 123% to 496%.
6	Gholampour et al. [78]	50% RFA	GGBS and fly ash	The RFA50 mix with 35% GGBS increased the CS: • At 7 days by 35.7%; • At 28 days by 36.3%. The RFA50 mix with FA23% and GGBS47% increased: • The modulus of elasticity (Ec) by 6.5%; • The STS by 7.3%. FA mixes showed a higher water absorption rate, and GGBS mixes showed a lower water absorption rate in the concrete specimens.
7.	Kumar and Singh [84]	RCA at 0, 25, 50, 75, and 100%	10% coal bottom ash and 50% fly ash	RCA specimens with 50% fly ash and 10% coal bottom ash reduced: • The CS by 4%, 8%, 11, and 9%; • The STS by 10, 17, 26, and 20% for the 25, 50, 75, and 100% replacement levels, respectively, at 90 days.

* CS, compressive strength; ** STS, splitting tensile strength.

Figures 5 and 6 show the variation in compressive and split tensile strength results after a curing period of 28 days in various studies. The effective use of recycled CDW in concrete production enhanced the circular economy and the consequences of that practice for a sustainable flow of resources. Mixed recycled aggregates (MRAs) comprise a substantial proportion of the total construction and demolition waste. The biggest obstacle to MRA recovery and recycling is its non-uniformity and several inherent qualities that directly affect the concrete's performance. The results of earlier studies indicate that the surface treatment caused a reduction in the water absorption rate of the MRA and improved its abrasion resistance. The treated MRA did not exhibit much of an enhancement in the mechanical properties, but the durability was found to be greatly enhanced [85]. From an engineering standpoint, recycled aggregate does not impede structural concrete members as the strength parameters of the RA keep improving.

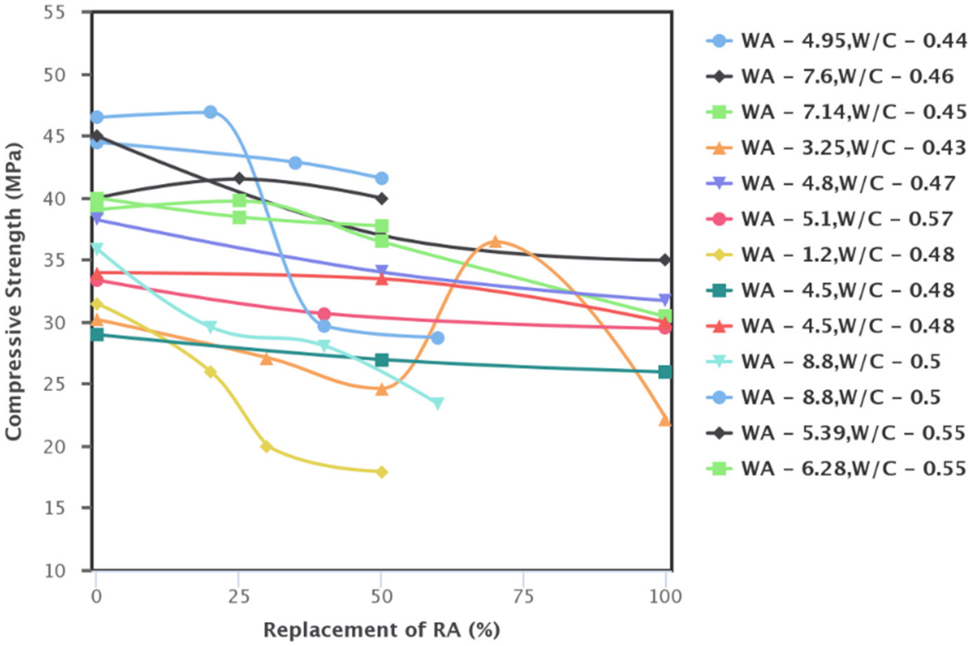

Figure 5. Results of studies on compressive strength on the 28th day ([33]** [44]* [77]* [86–89]* [90]* (60%GGBS, 60%GGBS and 7%Lime) [91]*, [91]* (10% SF), [92]**, [92] (CMRA)) * RCA, ** FRA.

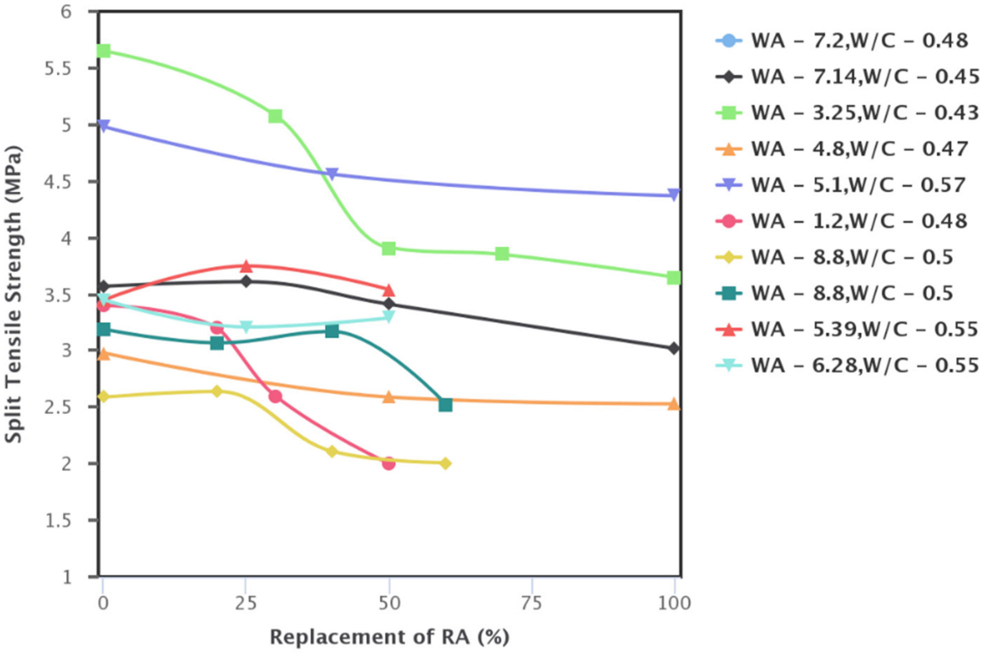

Figure 6. Results of studies on split tensile strength on the 28th day ([33]**, [44]*, [77]*, [88,89]*, [91]*, [91]* (10%SF), [92]**, [92] (CMRA), [93] (MRA)) * RCA, ** FRA.

2.5. Supplementary Cementitious Materials

The different supplementary cementitious materials exhibited improved performance in the recycled aggregate concrete. This section explains how authors utilized various additives and the ideal replacement proportion at which they work best. Based on the reported results, Table 6 summarizes the significance of the inclusion of coarse and fine recycled aggregates on the strength and durability properties. The improvement in strength was achieved with fly ash (FA) only at a later age (after 90 days). Unlike FA, the addition of GGBS and silica fume (SF) increased the early strength compared with the control mix. The early strength increases brought about by the addition of GGBS are due to sufficient amounts of lime and silica, which cause the GGBS to hydrate like Ordinary Portland Cement (OPC). When adding a small amount of SF (7% only) to RAC, the compressive strength of the concrete increased at an early curing age because of its capacity to permeate into the pores. SF is one of the most efficient materials and causes a 53% reduction in the permeability of chloride ions. FA, which has a higher alumina concentration, can mitigate the penetration of chloride ions, resulting in concrete with a higher electrical resistivity value compared with GGBS. Even though metakaolin is a pozzolana with 60.07% silica oxide, which is very high compared with OPC, the addition of 6.5% metakaolin to the recycled concrete aggregate mix showed no effect.

Table 6. Variation in the strength and durability of recycled aggregate concrete.

Literature	**Aggregate Type and Replacement Level**	**Admixture Dosage and Grade or W/C of Concrete**	**Admixture/ RA Optimum Dosage**	**CS** ↑↓	**STS** ↑↓	**FS** ↑↓	**RCPT** ↑↓	**WPT** ↑↓
	(%)	**(%)**	**(%)**	**MPa at 28 Days**			**Coulombs**	**mm or %**
Dimitriou et al. [93]	MRA (0, 50, 100)	W/C: 0.48	-	Up to 47.1 (−34.7%)	Up to 3.1 (−26.2%)	Up to 6.6 (−23.6%)	Up to 5248 (+51.1%)	-
	MRA (100)	FA: 25	-	35.6 (−50.6%)	2.0 (−52.4%)	6.3 (−26.7%)	Up to 5303 (+52.7%)	-
		FA: 25 and SF: 5	-	38.2 (−47%)	2.2 (−47.6%)	6.3 (−26.7%)	Up to (−0.2%)	-
Sivamani et al. [33]	FMRA 0, 25, 50, 100	W/C: 0.45	25	Up to 30.45 (−22.1%)	Up to 3.0 (−22.1)	Up to 3.86 (−11.9%)	Up to 4200 (+90.9%)	Up to 6.73% (+31.4%)
Khan et al. [88]	RCA 0, 30, 50, 70, 100	W/C: 0.43	30	Up to 22.22 (−26.5%)	Up to 3.65 (−35.4%)	Up to 4.03 (−38.5%)	-	Up to 30 mm (+200%)
Cantero et al. [94]	MRA 0, 25, 50 75, 100	Grade: 30 MPa	75	Up to 47.78 (−6.6%)	-	-	-	Up to 17 mm (+36%)
Yan et al. [95]	RCA 0, 30, 50, 100	W/C: 0.45	-	Up to 32.2 (−29.2%)	-	-	-	-
		calcined nano-attapulgite (CNAT): 2, 4, 6, 8	CNAT: 6%, RCA 50%	2% CNAT: Up to 35.3 (−27.2%) 4% CNAT: Up to 37.5 (−24.7%) 6% CNAT: Up to 38.5 (−19.9%) 10% CNAT: Up to 38.8 (−13.4%)	-	-	-	-
Bhasya et al. [89]	RCA 0, 50, 100	Grade: 30 MPa	-	Up to 31.74 (−17.0%)	-	-	Up to 3386 (+51.7%)	Up to 6.49% (+54.5%)
Saravanakumar et al. [96]	RCA 0, 25, 50, 100	Grade: 50 MPa	-	Up to 33.78 (−37.1%)	Up to 3.21 (−34.4)	-	-	-
		Fly ash (FA): 40, 50, 60	50%FA and 50% RCA	FA40%: Up to 27.41 (−26.3%) FA50%: Up to 26.74 (−19.7%) FA60%: Up to 22.23 (−17.1%)	FA40%: Up to 3.0 (−26.8%) FA50%: Up to 2.63 (−29.1%) FA60%: Up to 2.25 (−30.6%)	-	-	-

Table 6. *Cont.*

Literature	Aggregate Type and Replacement Level	Admixture Dosage and Grade or W/C of Concrete	Admixture/RA Optimum Dosage	CS ↑↓	STS ↑↓	FS ↑↓	RCPT ↑↓	WPT ↑↓
	(%)	(%)	(%)		MPa at 28 Days		Coulombs	mm or %
Dilbas et al. [91]	RCA 0, 20, 40, 60	W/C: 0.5	20% RCA	Up to 23.4 (−34.8%)	Up to 2.01 (−22.4%)	-	-	Up to 9.64% (+142%)
		Silica fume (SF): 5, 10	10% SF	SF 5: Up to 28.8 (−28%) SF 10: Up to 28.8 (−38.1%)	SF 5: Up to 2.6 (−13.1%) SF 10: Up to 2.5 (−21.0%)	-	-	SF 5: Up to 8.0% (+171.6%) SF 10: Up to 7.5 (+166.7%)
Barrag’an-Ramos et al. [97]	FRCA 0, 20, 60, 100	W/C: 0.45 and 0.50	20 FRCA	W/C: 0.45: Up to 26 (−16.1%) W/C: 0.5: Up to 23 (−11.5%)	-	-	W/C: 0.45: Up to 8500 (+34.9%) W/C: 0.5: Up to 6900 (+16.9%)	-
		FA: 20%	20FA	W/C: 0.45 Up to 22 (−29.0%) W/C: 0.5 Up to 17 (−34.6%)	-	-	W/C: 0.45 Up to 5900 (−6.3%) W/C: 0.5 Up to 7000 (+18.6%)	-
Ju et al. [98]	FRCA 0, 50, 100	Grade: 20 MPa	FRCA 50%	Up to 27.7 (−12.0%)	Up to 3.61 (−6.3%)	-	-	-
		FA: 15, 30 GGBS: 20,40 SF: 2.5,5	FA—30 GGBS—40 SF—5	FA 15: Up to 32.8 (+4.5%) FA 30: Up to 21.7 (−31.0%) GGBS 20: Up to 32.8 (+4.3%) GGBS 40: Up to 27.5 (−12.5%) SF 2.5: Up to 33.6 (+6.9%) SF 5: Up to 21.6 (−31.3%)	FA 15: Up to 3.9 (+3.0%) FA 30: Up to 3.6 (−6.5%) GGBS 20: Up to 3.70 (+4.1%) GGBS 40: Up to 3.58 (−7.2%) SF 2.5: Up to 4.03 (+2.7%) SF 5: Up to 2.64 (−31.6%)	-	-	-
Kirthika et al. [37]	FMRA 0, 30, 50, 75, 100	W/C: 0.50	30	Up to 30.1 (−16.9%)	Up to 2.9 (−6.45%)	Up to 4.6 (+2.22%)	-	-
Joseph et al. [4]	CMRA 0, 30, 60, 100	W/C: 0.42	30	Up to 34.92 (−18.7%)	Up to 2.21 (−19%)	Up to 2.52 (−47.4%)	-	-

Using RCA with a silica fume paste (ten parts water and one part solid) improved the interface between the aggregate and the surface of the RCA, resulting in denser hydrates that reduced the penetration of carbon dioxide. On the other hand, the fly ash slurry produced less effective results than the silica fume slurry. Mixing a 10% solution of silica fume with recycled concrete aggregate made the SF particles penetrate the loose mortar layer of the RA. When comparing ultrasonic cleaning of RCA to SF impregnation, the improvements in properties are smaller in ultrasonic cleaning [99]. The ultrafine cementitious material’s inclusion decreased the number of $Ca(OH)_2$ crystals, which was detrimental to the concrete’s properties. The addition of 10% superfine phosphorous slag (PHS) and 10% GGBS produced an improvement in the hardened properties of the concrete. Because of the increase in the hydration retardation produced by PHS, specimens with 20% phosphorous slag had a lower modulus of elasticity than the other specimens [58]. The utilization of pulverized coal bottom ash with a Blaine fineness of 858.6 m^2/kg, which is two times finer than cement, can significantly enhance the strength properties of concrete [100].

The addition of a 60% GGBS, 7% lime, and 100% RCA combination produced a dense microstructure compared with concrete without lime. The lime content in the GGBS was 29% less than that in OPC (64.40%). However, adding lime can increase the alkalinity of the concrete, resulting in the breakdown of GGBS particles and producing additional calcium hydrate (CSH) gel [90]. The addition of 1%, 3%, and 5% nano SiO_2 decreased the permeability, thereby reducing the penetration of chloride ions. The compressive strength of the 3% nano-silica substitution in 40% RCA was comparable to that of regular concrete at later ages. Calcium hydroxide combines with nano SiO_2 during the hydration of cement and serves as both an activator for the hydration reaction and a filler to increase the density [101]. Therefore, the modification method impacts upon the compressive strength of recycled concrete aggregates. In addition, incorporating supplementary cementitious materials helps to improve the hardened properties of recycled aggregates.

Figure 7 shows the variation in the water absorption and chloride ion permeability with the variation in the recycled aggregate replacement level in the concrete. Regarding mechanical and durability properties, similar results were obtained (up to 50% replacement of recycled aggregate with 25% pozzolanic materials). The addition of pozzolanic materials at the 45% replacement level in entirely replaced recycled aggregate concrete improved the mechanical and durability properties compared with conventional concrete [102]. The RFA concrete exhibited higher strength and less drying shrinkage than regular concrete after the inclusion of additional cementitious ingredients. The pozzolanic materials, such as fly ash and GGBS, effectively reduced the adverse effects of the recycled fine aggregates [103]. Therefore, supplementary cementitious materials could improve the strength and durability properties, reducing the difficulties associated with extensive pretreatment techniques for recycled aggregates.

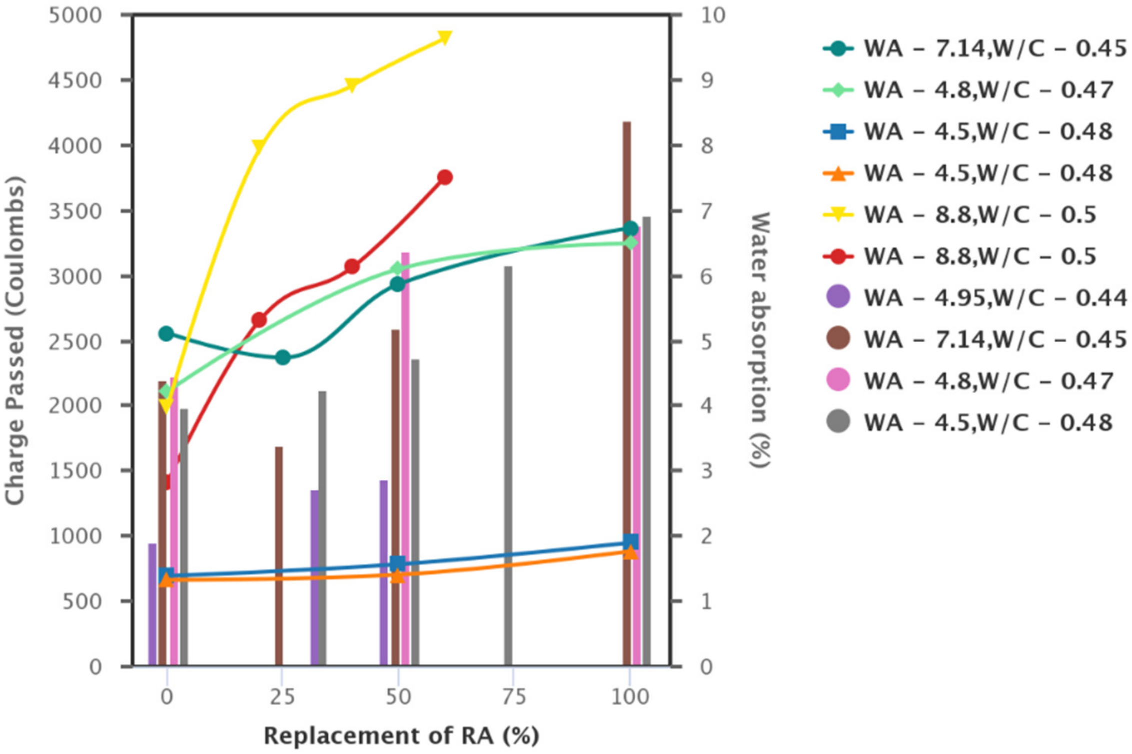

Figure 7. Variation in WPT and RCPT values of RA. ([33]**, [86]*, [88,89]*, [90]* (60%GGBS, 60%GGBS and 7%Lime), [91]*, [91]* (10%SF)) *RCA, **FRA.

2.6. Frost Resistance

The durability of RA concrete is typically lower than that of conventional concrete due to the old mortar on the RA concrete's surface. Several researchers have improved the adverse effects related to the durability of RA using various techniques. In general, the durability characteristics of recycled aggregate concrete, such as chloride ion permeability, water absorption, sorptivity, acid resistance, and frost resistance, decline as the RA material content increases. The durability aspects, such as the chloride ion permeability and the freeze and thaw resistance, can affect the mechanical behavior and development of the microstructure of RA concrete [104]. Adding GGBS and fly ash improved the frost resistance of recycled aggregate concrete. Recycled aggregate concrete without fly ash and GGBS began to lose mass after 25 freeze and thaw cycles. However, the independent or simultaneous replacement of fly ash and GGBS in 50% replaced recycled aggregate concrete delayed the mass loss rate only after 150 freeze and thaw cycles [86]. Similar research on durability aspects showed that, at up to the 40% replacement level, the durability factor value (98.4%) was slightly lower than that of conventional concrete. The change in length of 50% replaced recycled aggregate concrete was 10.9% larger than that of 30% recycled aggregate concrete after 300 freeze and thaw cycles. As a result, it was found that the durability characteristics were comparable with those of conventional concrete up to the 50% replacement level [105]. Additionally, the freeze and thaw resistance of recycled aggregate was tested based on the water absorption test. The water absorption of recycled aggregate concrete after 100 freeze and thaw cycles increased by 58.1% for 100% replaced recycled aggregate concrete due to the old mortar, which produced a weaker interfacial transition zone, leading to the transport of water into the concrete. Adding 40% ferronickel slag as a fine aggregate in 50% replaced recycled aggregate concrete decreased the water absorption value by 19.76%. This reduction was due to the reaction between the non-crystalline phases in the ferronickel slag, leading to the formation of a larger amount of secondary gel, which improved the weak interfacial zone in the recycled aggregate concrete [87]. The mass loss rate of the RA increased as the recycled aggregate content increased as shown in Figure 8.

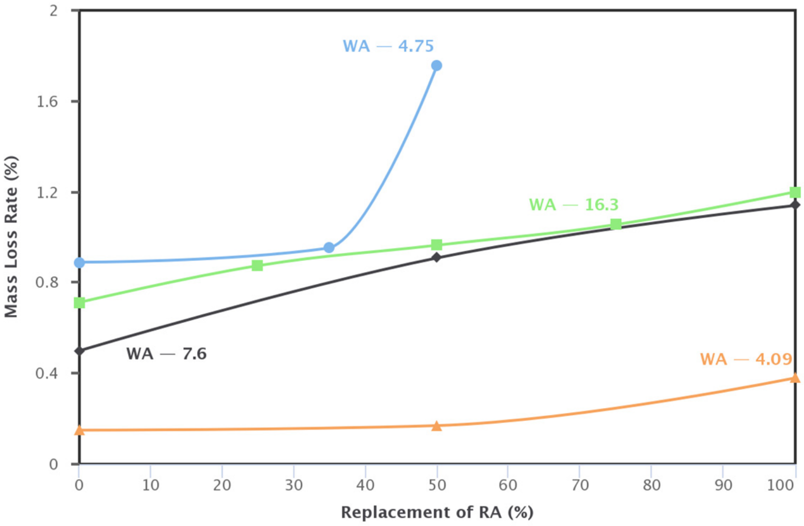

Figure 8. Mass loss rate of RA between 100 and 150 F–T Cycles [86,105–107].

The addition of pozzolanic materials could offset the increase in the mass loss rate. Adding 30% fly ash to recycled aggregate concrete improved the frost resistance by 30%. In addition, the frost resistance of 50% replaced recycled aggregate concrete with the simultaneous replacement of supplementary cementitious materials, such as 15% GGBS and 15% fly ash, exhibited better performance than conventional concrete [86]. Although the recycled aggregate content affects the freeze and thaw resistance, the addition of supplementary cementitious materials can enhance the freeze and thaw resistance to some extent.

3. Scientometric Review of Recycled Concrete Aggregate Research

The bibliometric data were obtained from the Clarivate Analytics Web of Science database. The search was systematic and extensive in order to ensure that the conclusions of the review are sound. The retrieval of the publications was done on 10 September 2021. Fundamentally, the article search was performed using the keyword parameters ((recycled concrete aggregate) and (strength)). The period was initially unrestricted. The number of articles returned due to this query was 3893 between 1965 and 2021. After applying filters for the period from 2012 to 2021, setting the language to English, and eliminating the review papers, proceeding papers, and early access papers, the total number of documents screened was 3209. Out of these 3209 documents, unrelated topics were eliminated manually, and only experimental studies on recycled aggregate concrete were selected. Finally, 1415 documents were selected for top-cited paper and keyword co-occurrence analysis. Clarivate Analytics Web of Science was used to retrieve the complete database. Furthermore, the output was visualized using the VOSviewer 1.6.17 software.

3.1. Top-Cited Articles

The relationship between a paper and its citations provides information about the document's quality. A high citation metric is directly proportional to high document quality, so researchers frequently refer to these documents. The top-cited document [1] describes the mechanical and permeability properties of recycled concrete aggregate. The second-most cited document defines a method for the addition of class F fly ash to mitigate the inferior properties of recycled aggregate concrete [108]. The third-most cited document reports valuable information on the durability effects and a method for the design of RAC [109]. Among the top 48 documents [110], is the most cited (nine times) by the top-listed documents. There are several documents [1,108,110–124] that were cited more than five times by the top-listed documents. Therefore, the listed documents are essential in the field of recycled concrete aggregate.

3.2. Keyword Co-Occurrence and Evolution Analysis

The soul of an article is its keywords, which can accurately and succinctly describe the research article. Accordingly, high-frequency keywords frequently identify the hot subjects in a specific research domain. VOSviewer's keyword co-occurrence network can show the degree to which a keyword appears in a set of papers. The co-occurrence and keyword analysis is done using all keywords as a unit of analysis. Web of Science gives keywords from the abstract and title using a function called "keyword plus" and the keywords given by authors. The standardization of keywords was necessary to eliminate the recurrence of similar terms and meanings. After eliminating common terms, the map visualization showed 13 clusters. Keywords with a high degree of connection with one another are more likely to be grouped together. The keyword grouping was necessary in order to represent the same topic within one cluster. The usage of the keyword and the increase in the font define the total link strength (TLS) [125]. From the 251 standardized keywords, keywords with more co-occurrences with generic topics, such as recycled concrete aggregates, properties, strengthening, performance, and evaluation, were manually removed.

In Figure 9, the portion in the middle of the visualization represents a strong relationship between those keywords. The higher density represents the well-developed research on the theme. The keywords in the outer area, such as "recycled aggregate concrete-filled steel tube", "fiber-reinforced polymer tubes", "tubular skin columns", "glazed hollow beads", "compacting concrete", "functionally graded concrete", "nano-sheets", "graphene oxide", "endurance limit", "strain rate", "sorptivity test", "frost resistance", "air content", "bottom ash", "sulphate attack", "bacterial", "oil fuel ash", "bagasse ash", "kiln dust", "dune sand", "manufactured sand", "calcium carbide residue", "wastewater", "time-dependent deflection", "fatigue strength", "seismic performance", "mixed recycled aggregates", and "precast industry waste", and many of these research fields tended to be immature. Still, more studies must be incorporated in order to develop cost-effective and efficient recycled concrete aggregates to conserve natural materials and minimize the accumulation of construction and demolition waste.

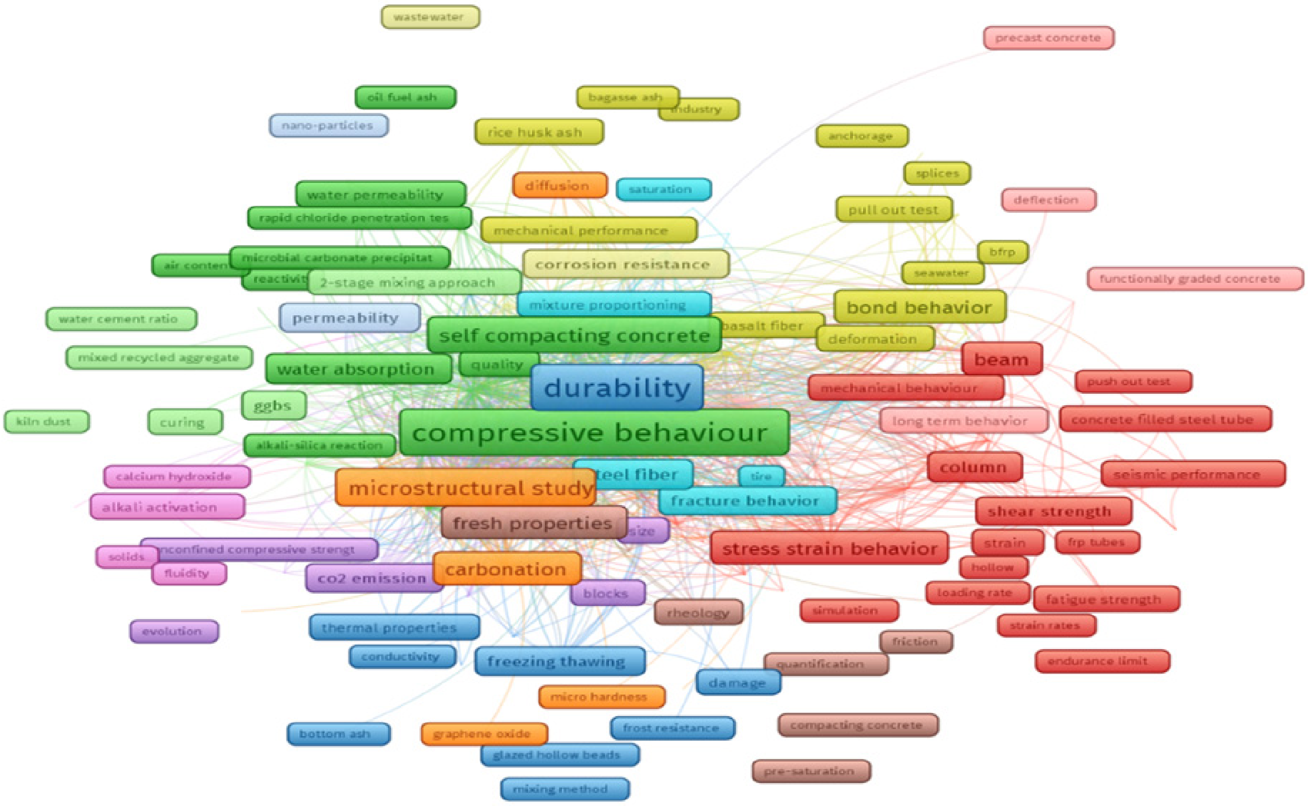

Figure 9. Visualization of the keyword co-occurrence analysis.

4. Current Trends and Future of Recycled Aggregates

The code IS 383:2016 mentions that the extension of the utilization of RCA for plain concrete should be up to 25%. Similarly, the code permits RCA usage for reinforced concrete up to 20%, and the grade of the concrete can be up to M25. This specification was updated in IS 383:2016 based on extensive research in the field of RCA. Still, there is scope to increase the replacement percentage of RCA and the usage of it in higher-grade concrete for the effective utilization of CDW, thus improving the circular economy in the construction field. Since IS code 383:2016 does not permit RA usage in both plain and reinforced concrete, further research on mixed recycled aggregates is needed in order to increase the use of all CDW materials effectively and efficiently. A detailed study on the durability factor of recycled aggregate concrete is necessary due to the heterogeneous behavior of recycled aggregates. Additionally, the development of standards is necessary to quantify the inherent features of RA. The lack of appropriate regulations, codes, and specifications limits the use of RA. So, research can be undertaken in the future to formulate standards that would enhance RA use, reducing the major environmental problems.

5. Discussion

People have become more concerned about environmental issues and pay more attention to the vast amounts of concrete trash that are created. Effective recycling processes and the use of concrete debris will enable the development of a sustainable circular economy. X-ray fluorescence test results show the presence of SiO_2, CaO, and Al_2O_3 in coarse and fine recycled aggregates. The natural aggregate seems to have a significant amount of SiO_2 and less CaO and Al_2O_3, whereas the recycled aggregate has a similar amount of SiO_2 and slightly higher CaO and Al_2O_3 content. The results of studies on recycled aggregates suggest that their compositions are comparable and connected to the source concrete [38].

However, recycled aggregate made from construction and demolition waste must be cleaned and treated properly before it can be used in concrete mixes. Furthermore, recycled aggregate typically contains old mortar; as a result, techniques for the improvement of inferior properties and the reduction of impurities are necessary.

Recycled aggregate used as a partial aggregate replacement typically affects the workability of fresh concrete because of its higher water absorption [126]. However, the soaking of the recycled aggregate, the use of the water compensation method during mixing [127], and the addition of a superplasticizer could minimize the negative effect on the workability. Nevertheless, based on the reported studies, the use of an aggregate made from construction and demolition waste generally decreased the strength and durability attributes. The weaker interface that increased the water absorption and the old mortar that decreased the bonding strength were the leading causes of the decline in strength. As a result, adopting a high recycled aggregate replacement level is generally not advised; according to the literature, it should be kept below 30%. Table 7 shows the strengths and weaknesses of various treatment techniques for recycled aggregates.

Table 7. Strengths and weaknesses of pretreatment techniques.

S. No	Pretreatment Technique	Advantages	Disadvantages
1	Nano-silica coating of RA [79]	✓ Absorption of nano-scale materials on the surface leads to a denser interfacial transition zone.	✓ Accumulation of nanoparticles leads to a non-uniform distribution. ✓ High cost of nanomaterials.
2	Chemical and impregnation treatment (sodium silicate, silane slurry, and polyvinyl alcohol) [128]	✓ More compact and stable ITZ. ✓ Recycled aggregate with sodium silicate and silane impregnation resulted in an increase in hydration products.	✓ Ternary blended impregnation is less effective due to the formation of a hydrophobic layer by the polyvinyl alcohol solution, which acts as a barrier for the compact microstructure.
3	Pozzolanic slurry impregnation (fly ash, GGBS, silica fume, and metakaolin) [129]	✓ Economical treatment method. ✓ Improved the bond between the new mortar and the recycled aggregate due to the increased pozzolanic reactivity.	✓ Increased amount of silica fume produces an insufficient interfacial transition zone. ✓ Addition of pozzolanic materials reduces the workability.
4	Carbonation treatment [130]	✓ The deposition of calcite in the pores present in the recycled aggregate leads to a denser surface.	✓ The enhancement in the quality of the carbonated recycled aggregate depends on many factors, such as the vacuum pressure, CO_2 concentration, and the duration of the treatment.
5	Heat and mechanical rubbing [131]	✓ The friction between the cement and the aggregate is improved. ✓ Effective in the detachment of adhered mortar in the recycled aggregate.	✓ Increased temperature leads to the disintegration of the recycled aggregate. ✓ Problems related to uneven heating lead to worse performance.
6	Acid treatment followed by mechanical grinding [66]	✓ Soaking in mild acid improved the bonding without changing the chemical disintegration. ✓ Mechanical treatment efficiently removed the loose particles on the surface of the recycled aggregate.	✓ A controlled environment is necessary in order to carry out the mechanical rubbing. ✓ Although mild acid handling is not that problematic, proper handling is still necessary.

Table 7. *Cont.*

S. No	Pretreatment Technique	Advantages	Disadvantages
7	Bio deposition [132]	✓ The addition of bacteria to the recycled aggregate produced a different and effective morphology in the calcite phase.	✓ During the dissolution of certain bacteria, there is the possibility that ammonia will be produced, which is harmful and can corrode the reinforcement. ✓ The outcome of the treatment will be dependent on the type of bacteria, the number of bacteria added, and the temperature.

Due to the existence of porous mortar, prior research has found that using recycled aggregate in concrete negatively affects its microstructural behavior and durability attributes. Therefore, adding mineral admixtures, such as fly ash, GGBS, metakaolin, and silica fume, is necessary in order to improve the negative effect of recycled aggregate concrete, which is due to the filler effect and the improved pozzolanic reactivity of the cement that increases its strength. However, techniques such as the inclusion of additional cementitious materials in the right amounts not only act as a filler but also aid in the hydration reaction, increasing the number of hydration products, decreasing the amount of pore space in the concrete, and resulting in recycled aggregate concrete with a more compact structure and higher strength and durability [133]. Still, the properties of RA vary so widely among the sources that it needs more testing before it can be utilized in the broad sense of concrete applications.

6. Conclusions

This paper discusses the properties of recycled aggregate, fresh concrete, and hardened concrete and the capacity of various treatment approaches to improve the inferior properties of recycled aggregate. The following issues were identified after a careful examination of the recycled aggregate concrete research:

- The water absorption rate of recycled concrete aggregate can be reduced using various methods, such as carbonation treatment, the addition of supplementary cementitious materials with a two-stage mixing approach, hydrochloric acid, H_2SO_4 acid, and acetic acid immersion treatments, impregnation with calcium metasilicate, the addition of pozzolanic slurry (nano-SiO_2, silica fume, and fly ash slurry), the addition of a superfine powder (phosphorous slag, ground granulated blast furnace slag, and fly ash) with a superplasticizer, heating–scrubbing, and the immersion of RCA in a crystallization agent.
- We discuss the strengths and weaknesses of each improvement method, including the mixing approach, acid treatment, carbonation treatment, and the addition of pozzolanic material. The addition of pozzolanic materials and pre-soaking using nanomaterials effectively and economically improved the detrimental effects of recycled aggregates.
- The optimum level of replacement of different pozzolanic materials with recycled concrete aggregate was found to be 7% for silica fume, a liquid-to-solid ratio of 10:1 for silica fume slurry, a combination of 10% superfine phosphorous slag with 10% GGBS, a combination of 60% GGBS and 7% lime, and 3% replacement of nano-silica. In addition, a combination of fly ash, slag, and silica fume was found to mitigate the adverse effect of RCA and improve the mechanical properties.
- The top-cited articles and keyword co-occurrence visualization provided us with the most- and least-studied areas, which may help us to improve the research field further.

As recycled aggregate is similar to natural aggregate, the material can be utilized as a fine and coarse aggregate if the proper enhancement techniques are adopted. Moreover, based on the literature, adequate workability and strength in a concrete made from recycled aggregate could be attained at up to the 30% replacement level. Furthermore, durability properties could be enhanced with the addition of various supplementary materials and treatment methods even in high-strength concrete, as the properties keep improving over the curing period. By doing so, a significant amount of building and demolition waste could be used, which could help to reduce the use of virgin materials in the construction sector in order to protect the environment.

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