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Review

Performance Improvement of Recycled Concrete Aggregates and Their Potential Applications in Infrastructure: A Review

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Abstract: In the construction industry, natural aggregates (NA) can be replaced by recycled concrete aggregates (RCA), which can address the issue of construction-waste disposal and resolve the dilemma between demand and supply. This paper aims to systematically review the modification of RCA techniques and their application in producing recycled aggregate concrete (RAC). First, the pretreatment approaches for enhancing the properties of RCA are introduced. Next, the improved efficiency of these approaches and their influences on the workability, mechanical strengths, and permeability of RAC are analyzed and discussed. Subsequently, the effectiveness of different techniques and their cost/environmental impact are compared. Finally, some case studies of the application of RCA in infrastructure are presented, and the remaining challenges and perspectives are discussed. The results of this review work can extend the knowledge of RCA and RAC, as well as serving as a source of inspiration for further studies.

Keywords: adhered cement mortar; recycled aggregate concrete; pretreatment methods; sustainable cementitious composites; green cement concrete

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1. Introduction

The construction industry is a major consumer of natural resources, with global virgin aggregate production expected to rise to approximately 60 billion tons in 2030 [1–3]. Simultaneously, construction and demolition (C–D) waste accounts for a large portion of solid waste, and its consumption is increasing rapidly worldwide [4–6]. The recycling of C–D waste is a key issue in the sustainable development of concrete [7,8], which can address the C–D waste disposal problem and the dilemma of aggregate demand–supply. Recycled aggregate concrete (RAC) is the aggregate obtained by the crushing, cleaning, and grading of concrete-waste structures. The reuse of concrete waste as an aggregate to produce new RAC is a promising strategy to address the shortage of natural aggregate (NA) resources, which may be a solution to the dilemma created by the huge amount of idle concrete waste, as well as decreasing the depletion of natural resources and preserving the environment [9–11]. By removing the adhered mortar from RCA, high-quality RCA is produced and reused in structural concrete, thus ensuring the complete recycling of C–D wastes. As illustrated in Figure 1, high-quality RCA can be used in ready-mixed or precast concrete, while separated fine/powdered mortar can be used as a cement-replacement material.

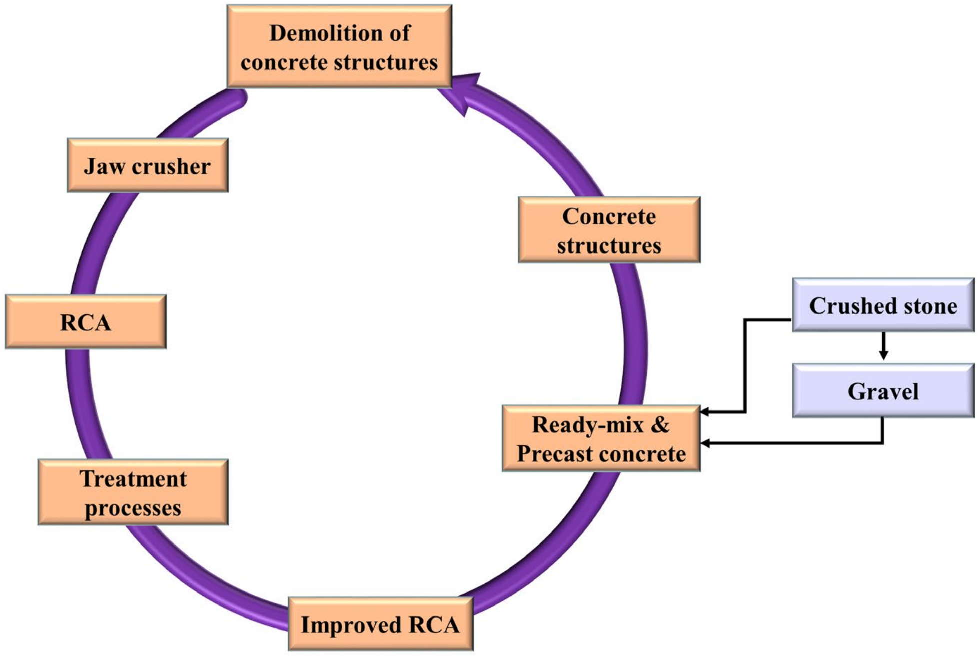

Figure 1. Schematic flow of concrete-recycling system [9].

Typically, RCA comprises a virgin aggregate and adhered mortar, and the old adhered mortar exhibits a loose and porous character [6,7]. The volume of adhered mortar around the RCA varies from 25% to 60%, depending on the type and size of the RCA [3,6], as shown in Figure 2a,b. Therefore, the water absorption of recycled concrete aggregate (RCA) is 30–200% higher than that of the NA [7]. Additionally, the crushing method significantly affects the shape and texture of the RCA, and the crushing process may also produce new micro cracks in RCA. It is widely believed that the presence of porous mortar in RCA leads to the appearance of weak interfacial transition zones (ITZ, see Figure 2c), which, in turn, affects the properties of RAC [12–15]. Typically, replacing NA with RCA reduces the workability of fresh concrete and results in lower strength and durability, as well as an increase in the shrinkage of hardened concrete [16–18]. These drawbacks limit the wide application of RCA in structural concrete. Therefore, improvements in RCA quality and increases in its application in structural concrete are necessary. Currently, there are two main pathways for producing high-quality RCA [7–9]: (1) removing the adhered mortar from the RCA surface and (2) strengthening the adhered mortar. According to these two methods, numerous studies have explored the elimination of or compensation for the negative influence of RCA in RAC production. Campaigners for sustainable environments and government organizations are interested in enhancing the quality of RCA and utilizing it to replace concrete production [9].

This review aims to summarize the published papers on RCA-pretreatment approaches, highlight the advantages of the pretreatment techniques, and examine their potential applications in the construction industry. Improvements in the quality of RCA can be obtained, and its influence on the workability, mechanical strength, shrinkage, and permeability of concrete are analyzed and discussed. Subsequently, the effectiveness of different methods and their cost/environmental impact are compared. Finally, some case studies of the application of RCA in structural concrete are summarized, and the prospects for future work are discussed. The results of this review work can extend the knowledge of RCA and RAC, as well as serving as a source of inspiration for further studies.

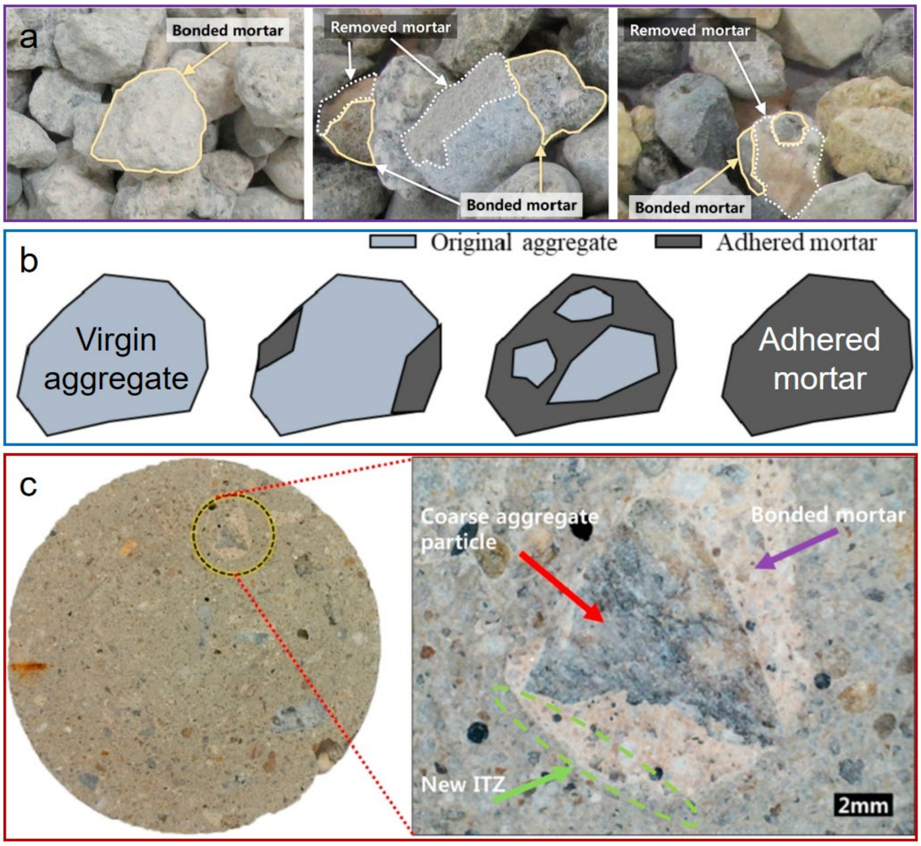

Figure 2. (**a**) Optical images of RCA: (**left**) RCA, (**middle**), RCA subjected to pretreatment by sodium-sulfate solution, and (**right**) RCA treated by HCl solution [15]; (**b**) types of RCA, depending on the adhered mortar [2]; and (**c**) images of the cross-section of the hardened concrete sample [15].

2. Pretreatment Methods for Improving the Properties of RCA

As mentioned above, RCA consists of the original aggregate and the adhered mortar; the latter is the fundamental reason for the inferior quality of RCA [19–21]. Therefore, removing the adhered mortar from the RCA or strengthening it are the two typical approaches for improving its properties, as shown in Figure 3 and discussed below:

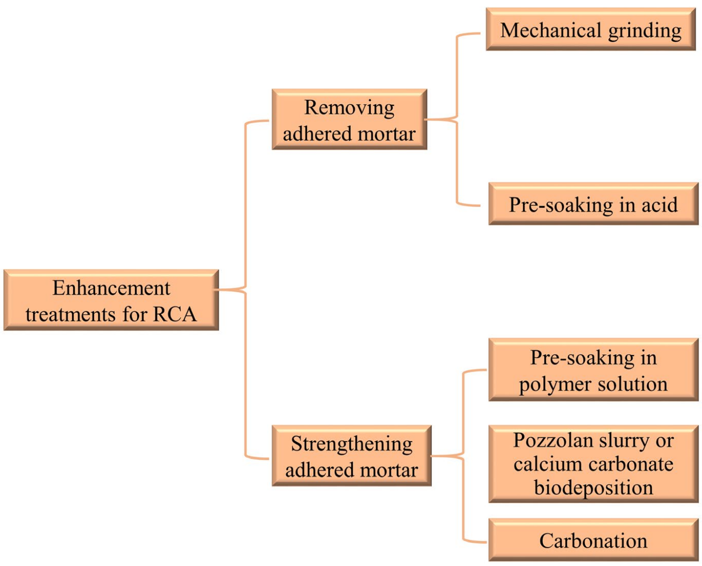

Figure 3. Enhancement treatments for RCA.

2.1. Removal of Adhered Mortar

According to previous studies [1,4,7,9], mechanical milling and the soaking of RCA in an acid solution are two common approaches to removing old adhered mortar from RCA. This section introduces and discusses the principles, advantages, and disadvantages of these two methods.

2.1.1. Mechanical Grinding

The use of crushing and ball milling can typically remove old mortar from RCA surfaces, as shown in Figure 4a.

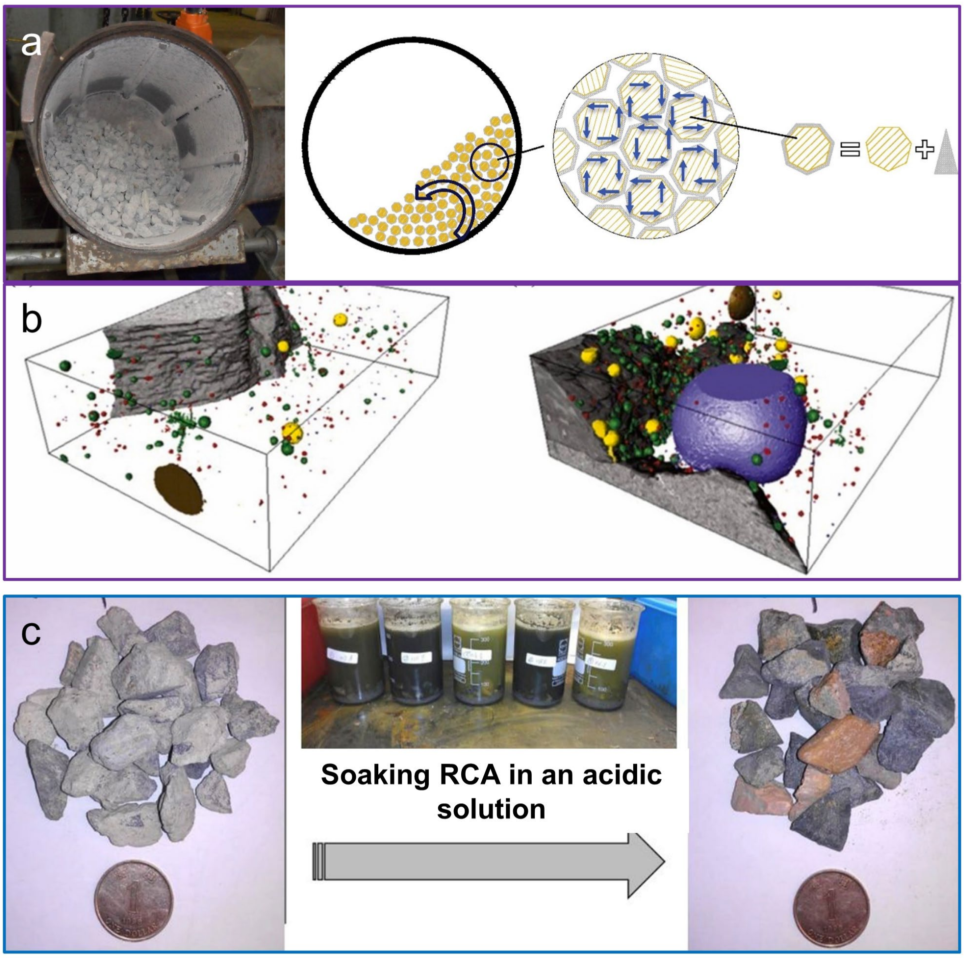

Figure 4. Removal of adhered mortar from RCA surface: (**a**) mechanical grinding [22]; (**b**) pore distribution in the original mortar (**left**) and crushed mortar (**right**). The different ball colors are different pores [3]; and (**c**) RCA-treated with an acid solution [23].

Interestingly, the shape of the RCA can be optimized with the help of the peeling-off effect, reducing the aspect ratio of the RCA and making the RCA's shape more uniform. The mechanical grinding method includes three types [24]. (1) Traditional mechanical grinding: this approach is achieved by the rolling vibration effect of the eccentric gears rotating at high speed in the grinder. The stripping efficiency and the RCA quality can be further improved by increasing the eccentric gear. (2) Selective heat grinding: the bonding strength between the mortar and the virgin RCA can be weakened with the assistance of microwave heating (Figure 4b), and subsequent mechanical grinding is applied to remove the adhered mortar. (3) Higher temperatures are beneficial for removing the adhered mortar from RCA. Typically, RCA is heated at 300–500 °C to make the old mortar more brittle and before grinding it. One should note that RCA's properties may be degraded when the temperature exceeds 500 °C [2,4]. Therefore, the selection of heating temperatures should be careful and rational to avoid significantly impairing the RCA's properties [6,7].

2.1.2. Pre-Soaking of RCA in Water/Acid Solution

The RCA is pre-soaked in water and impurities can be separated on its surface [25]. Although this approach can wash away weak mortar, most of the adhered mortar persists. Therefore, the soaking of RCA in various kinds of acid solutions to remove the old mortar has been studied (Figure 4c), based on dissolving the cement hydrates in the old mortar in an acid solution [15,26]. For example, Tam et al. [26] compared three types of acid solution (0.1 mol) to remove the mortar, and the experimental results revealed that HCl was the most effective acid for dissolving the adhered mortar. However, the increase in chloride and sulfate content of RCA after soaking in an acid solution and the increased costs of concrete production are obstacles to the implementation of this method.

Overall, mechanical milling or grinding is a popular treatment method for removing the adhered old mortar from the RCA surface because it has the benefits of ease of operation, environmental friendliness, and low cost compared to the soaking of RCA in an acid solution. However, mechanical grinding can easily lead to the degradation of RCA quality due to the introduction of microcracks by grinding. Therefore, a suitable treatment process needs to be selected with a balance among RCA quality, treatment cost, and treatment efficiency.

2.2. Strengthening of Adhered Mortar

Strengthening the adhered mortar is another strategy for enhancing the properties of RCA [27–30]. In addition to using polymer emulsion and pozzolan slurry to enhance the RCA quality, sodium-silicate solutions can generate water-repellent films on the RCA surface and fill the pores. Calcium-carbonate deposition and accelerated cement-hydrate carbonation can fill the old mortar's microcracks [8,27]. These methods are discussed in the following sections.

2.2.1. Polymer Emulsion

Some polymer emulsions can solidify quickly and improve the properties of RCA [8,31,32]. In particular, polyvinyl alcohol (PVA) is water-repellent, and it can fill the pores of the old mortar and seal the RCA's surface, thus decreasing the water absorption of RCA [33,34]. Furthermore, PVA impregnation can also improve the ITZ quality and enhance the performance of concrete [33–35]. Silicon-based water-repellent polymers can penetrate old mortar and form a crosslinked film with excellent water-repellent ability. However, the compressive strength of this type of concrete may be decreased due to the silane-hydrolysis characteristic.

In general, polymer treatments can enhance RCA quality (e.g., water absorption and density) and thus improve concrete's workability, shrinkage, and penetration resistance. However, the formation of a water-repellent film can degrade ITZ quality.

2.2.2. Sodium-Silicate Solution

Some hydration products (e.g., CH and C-S-H) are present in the adhered mortar of the RCA, in which the CH can react with sodium-silicate solution to generate C-S-H [36–38]. The reaction process is as follows:

$$\mathrm{Na_2SiO_3 + Ca(OH)_2 + H_2O \rightarrow C-S-H + NaOH} \tag{1}$$

In addition to generating more C-S-H, sodium-silicate solutions can form continuous layers on RCA surfaces [39,40]. However, excessively high concentrations of sodium-silicate solution may impair aggregate quality.

2.2.3. Pozzolan Slurry

Typically, the negative influence of admixed RCA on concrete's performance can be mitigated by introducing some mineral materials [41–45]. Generally, RCA is coated within a pozzolanic material slurry layer, which can fill the pores/voids inside old mortar and, thus, react with CH to generate C-S-H [46–51].

In general, the efficiency of this modification depends on the particle sizes of mineral materials, the CH content in the adhering mortar, and the reactivity of the pozzolan slurry [52–56]. Therefore, nano silica with a smaller size and high reactivity is more beneficial for enhancing the performance of RCA. However, the high-cost and challenging dispersion of nano-SiO_2 somewhat limits large-scale RCA enhancement and its practical applications.

2.2.4. Calcium-Carbonate Bio-Deposition

The bio-deposition of calcium carbonate on RCA surfaces is based on the ability of bacteria to precipitate calcium carbonate on the surfaces of cells (Figure 5a) [57]. This can be reflected as follows:

$$\mathrm{Sp.cell} + \mathrm{Ca}^{2+} \rightarrow \mathrm{Sp.cell} - \mathrm{Ca}^{2+} \tag{2}$$

$$\mathrm{CO(NH_2)_2} + 2\mathrm{H_2O} \rightarrow 2\mathrm{NH_4}^{+} + \mathrm{CO_3}^{2-} \tag{3}$$

$$\mathrm{Sp.cell} - \mathrm{Ca2}^{+} + \mathrm{CO_3}^{2-} \rightarrow \mathrm{Sp.cell} - \mathrm{CaCO_3} \tag{4}$$

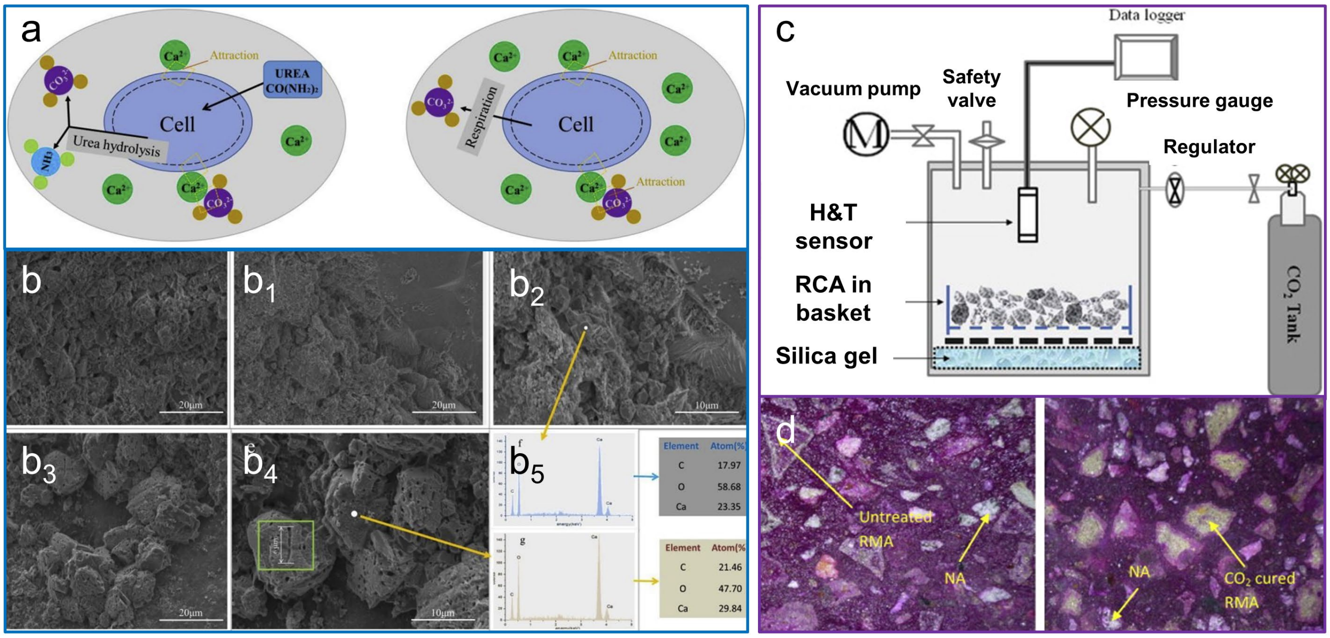

Figure 5. Strengthening of adhered mortar: (**a**) bio-deposition process: (left) bacterially induced $CaCO_3$ precipitation by urea hydrolysis and (right) $CaCO_3$ precipitation [57]; (**b**) SEM images of RCA: (**b$_1$**,**b$_2$**) RCA; (**b$_3$**,**b$_4$**) bio-deposition-RCA; (**b$_5$**) EDS of RCA in (**b$_4$**); (**c**) CO_2 curing experiment. T = temperature, H = humidity [27]; and (**d**) phenolphthalein spraying on concrete (left) with RCA and (right) with treated RCA [27].

Cells of S. pasteurii can attract Ca^{2+} and produce calcium carbonate [58,59]. Simultaneously, ammonia ions can increase the pH of the surrounding hydrated environment, which in turn increases the precipitation efficiency of calcium carbonate (Figure 5b).

2.2.5. Accelerated Carbonation

As presented in Figure 5c,d, CO_2 can react with adhered mortar (i.e., some hydrates, such as CH and C-S-H) [60–63]. Typically, the carbonation of CH and C-S-H can increase the solid volume by ~10% and 20%, respectively [64–66]. Therefore, carbonation can reduce RCA's porosity. The reaction process is as follows:

$$CH + CO_2 \rightarrow CaCO_3 + H_2O \quad (5)$$

$$\text{C-S-H} + CO_2 \rightarrow CaCO_3 + SiO_2 + nH_2O \quad (6)$$

The CH in the hydrated paste cannot react completely. Therefore, the calcium carbonate produced by carbonation can form a dense film around the CH [27,67,68]. The further dissolution of CH and the further diffusion of CO_2 are more difficult [61–63,69]. Thus, the CH's carbonation rate may be initially more rapid than that of the C-S-H [61,69,70].

3. Properties of RCA and PAC after Pretreatment

3.1. Properties of RCA

As given in Table 1, the pretreatment approaches are expected to improve the RCA quality, thus enhancing the performance of RAC. Therefore, this section summarizes the effects of pretreatment approaches on RCA's surface properties, porosity, and strength.

Table 1. Enhancement of RCA properties.

Treatment Methods	Mortar Removal (%)	Improvement Effect
HCL solution [71]	-	The mortar on the RCA surface is removed
Heated at 250 °C [72]	-	
Silicon-powder solution [73]	-	Decrease in water absorption and increase in apparent density
Fly-ash solution [73]		
Phosphate solution [74]	1.3	The formation of new precipitates of hydroxyapatite material makes RCA denser
CO_2 [75]	6.92	The microstructure of the RCA surface is denser
CO_2 [73]	-	
Biodeposition [59]		
PVA impregnation [76]	-	

3.1.1. Surface Properties

The surface properties of RCA greatly affect concrete's fresh properties [7,8]. Pretreating RCA can change its surface properties and, thus, affect the performance of concrete [3,4,7]. Therefore, this section discusses the pretreatment process's effect on RCA's surface properties.

Morphology and Microstructure

Generally, the texture of RCA is rough and non-homogeneous. Figure 6a,b present the 3D images of NA and RCA. As can be seen in the images, the surface textures of the NA and RCA are very different, while the color differences in the two-dimensional (2D) cross-sections reflect the variation in the internal density (Figure 6c,d). As indicated in Figure 6e, the surface of the RCA is covered with porous residual mortar and much fine debris. The rubbing of acid-treated RCA by mechanical means results in a more compact and smoother surface due to the removal of more loose material.

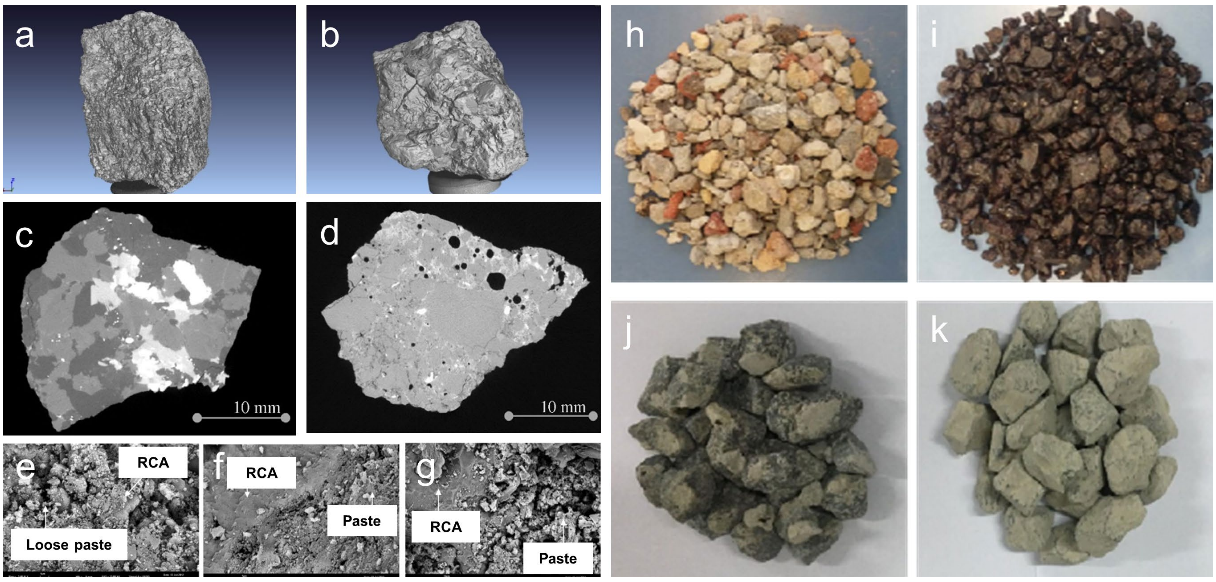

Figure 6. Surface texture of RCA—3D-scanner analysis of aggregates [22]: (**a**) NCA; (**b**) RCA; (**c**) 2D image of NCA and (**d**) RCA [22]; surface microstructures of aggregates [28]: (**e**) RCA; (**f**) RCA with 0.1 M HCl; (**g**) RCA with 0.8 M HCl; (**h**) RCA before coating and (**i**) after coating with polymer [77]; (**j**) RCA before coating and (**k**) after coating with cementitious slurry [78].

Figure 6f shows that the use of 0.1 M of acid solution can dissolve the adhering mortar from the RCA surface, making it more homogeneous. However, when the concentration of the acid solution was increased to 0.8 mol, it caused the RCA to become brittle and friable. It even eroded the surface of the adhered mortar, creating larger pores (Figure 6g). After immersion in the polymer solution and sulfur-aluminate cement slurry, the RCA surface was coated with a waterproof film (Figure 6i) and a cement-slurry overlay (Figure 6k); these two kinds of layer can fill the cracks and pores of adhered mortar. Compared with the untreated RCA (Figure 6i), the roughness of the RCA surface treated with the pozzolanic slurry almost disappeared (Figure 6k). After the carbonation and microbial carbonate precipitation treatment, a thick layer of product can be produced on the RCA surface. The quality of RCA improvement mainly depends on the microbial carbonate precipitation's treatment rate, growth environment, and culture conditions. Therefore, the surface roughness of RCA treated with microbial carbonate precipitation needs further systematic study.

Shape

The various geometric features of RCA include its round, angular, spherical, elongated or lamellar shape [1,4,7]. As shown in Figure 6h–k, the shape of RCA is generally flat and irregular. The shape index and flake index can quantify the shape of RCA, which is mainly influenced by the crushing process and impurities. The removal of the adhered mortar from RCA produces a finer particle-size distribution, with smaller and more elongated spheres, while strengthening methods, such as the treatment of RCA with microbial precipitation, carbonation, and polymer impregnation, has little effect on its shape.

3.1.2. Density

According to previous studies [3,4,9], the specific gravity of NA and RCA is between 2.4–2.89 and 1.9–2.7. Removal approaches can improve the density significantly. The combined usage of H_2SO_4 solution and mechanical grinding can significantly increase the density of RCA up to about 7% [26,79]. The density of RCA varies widely, from 3.8% to 4.4%, and it is close to the mass of pozzolanic slurry when immersed in it. The cement hydrates generated by bio-deposition and accelerated carbonation can fill some pores inside RCA [59,80,81]. However, their effect on density enhancement is lower than that of pozzolanic slurry [82–84].

3.1.3. Water Absorption

The soaking of RCA in an acid solution and mechanical grinding can remove old adhered mortar from RCA surfaces and, thus, reduce the water absorption of RCA [42,85,86]. Different kinds of acid solution, such as hydrochloric acid and phosphate acid, have been extensively adopted to remove adhered mortar from RCA surfaces [26]. For instance, the immersion of RCA particles in sulfuric acid solution can remove about 6% of mortar, which is better than the nitric solution. According to previous studies [6,7,26], the treatment method, the type and concentration of the acid solution, and the soaking time greatly reduce RCA's water absorption. Note that excessive pre-treatment methods, such as highly concentrated acid solutions, prolonged immersion, or relatively high temperatures, may erode RCA surfaces and lead to elevated water absorption. After the over-pretreatment, the microstructure of the adhered mortar demonstrated more porosity, as shown in Figure 6g.

After immersion in polymer solution, RCA's water absorption can greatly decrease compared to other pretreatment methods [34,36,44]. According to previous studies [33,34,39], paraffin impregnation showed the highest efficiency, of about 80%. The efficiency of the pozzolan-ash reaction is affected by the RCA size, the CH amount in the adhered mortar, and the reactivity of the pozzolan-ash material [28,30,77]. For example, the coating of cement@silica nanomaterials or silica-fume solutions on the surfaces of RCA can reduce its water absorption by 10–45% [78,87]. In conclusion, improvements in the quality of the coating of cementitious slurry are conducive to decreases in the water absorption of RCA. Typically, the precipitation of calcium carbonate produced by bacteria is affected by several key points [57]: the concentration of calcium ions, the pH, and the availability of crystal-nucleation sites. The deposited $CaCO_3$ particles that completely cover the RCA's surface area can decrease the RCA's water absorption. The carbonization efficiency is mainly influenced by the material properties, CO_2 concentration, and pressure [23,27]. In general, larger open porosity and suitable carbonation conditions are favorable for improving the quality of RCA [27,63,69].

3.1.4. Porosity

According to previous studies [3,5,7,62], the porosity variation in RCA is mainly affected by the composition and the content of adhering mortar. The porosity of RCA can be indirectly determined by water absorption, mercury intrusion pores (MIP), and computed tomography.

Previous studies suggested that the removal of the adhered mortar from RCA can decrease its porosity by 10–20%, and that this is mainly governed by the type of acid and the treatment time [3,5,6]. Generally, the removal approach can result in a porosity of RCA below 20%. However, excessive treatment (high acid concentrations or long soaking times) may increase the porosity of RCA [6,7]. Pozzolanic cementitious slurries can coat RCA surfaces, resulting in decreases in RCA porosity [59]. As demonstrated in published studies [62,63,69], carbonation can reduce the porosity of RCA by 20–50% [23].

3.1.5. Crushing Value

Generally, the crushing value represents the strength of the RCA [5,7]. The factors affecting the treatment efficiency of the use of acid solutions on RCA mainly include the acid concentration and soaking time. For instance, Tripathi et al. [88] suggested that the acid treatment of RCA requires a reasonable choice of acid concentration and soaking time to avoid damage to the RCA. Ismail et al. [28] showed that the suitable HCl-solution concentration for treating RCA was 0.1 mol. As reported by previous studies [46,78], the crushing value of RCA coated with sulphoaluminate cement or cement slurry was greatly reduced, by 10–20%. If an excessively thin coating paste is used, the inferiority of the adhered mortar cannot be ameliorated [78]. Carbonation treatments can enhance RCA mortar, and the adhered mortar's average microhardness can be enhanced by about 15% [62]. Generally, longer carbonation times are beneficial for improving RCA's crushing value.

3.1.6. Los Angeles Abrasion Resistance

The hardness of the RCA is the abrasion resistance, as generally determined by the Los Angeles (L.A.) Abrasion Tester [5–7]. Typically, the higher the L.A. abrasion value, the worse the abrasion resistance of the prepared RAC. These variations are mainly determined by the quality of the original material (namely, the concrete strength) and the content of the adhering mortar. In general, heat treatment, mechanical grinding, and acid solutions can decrease the L.A. abrasion values of RCA by about 35%, 30%, and 30%, respectively [51,55,89]. However, few studies have been conducted on the effect of accelerated carbonation techniques on the L.A. abrasion values of RCA.

3.2. Properties of RAC

3.2.1. Workability

The slump test is typically adopted to assess the workability of concrete (RAC in this review) in its fresh state. In general, the introduction of RCA results in a decrease in concrete slump, which is mainly attributed to the adherence of old mortar on the RCA surface and the multi-angular characteristics of the RCA [22]. When the surface texture of the RCA is more angular and rougher, increased intergranular friction can occur, thereby decreasing the workability of the RAC. Ismail et al. [28] used RCA by removing the adhered mortar, and they reported no significant change in a slump between mixtures made with virgin RCA and acid-treated RCA. Additionally, the RCA's moisture state is a major indicator affecting the workability of the mixture. The addition of moisture can increase the unit-water amount in RAC, decreasing the yield stress and leading to high slump values.

3.2.2. Mechanical Strengths

According to previous studies [82,90–93], the admixture of the higher replacement rate of RCA in concrete results in lower compressive strength, mainly due to the increase in the amount of the adhered mortar, making the ITZ region weaker [86,94–97]. Typically, lower amounts of adhered mortar and higher densities of RCA contribute to the enhancement of the strength of RAC, which theoretically depends on the efficiency of the removal of the adhered mortar from the RCA surface [98,99].

Some acid solutions, such as HCl, H_2SO_4, HNO_3, H_3PO_4, or $C_2H_4O_2$, have different abilities to remove adhered mortar from RCA surfaces, thus improving the compressive strength of RAC, as shown in Figure 7a. Note that the suitable soaking time for RCA in acid solutions should be carefully determined to remove loosely adhered mortar. Each of the different PVA concentrations used for RCA pretreatment has an optimal amount for enhancing RAC strength [33,36]. The beneficial effect of PVA impregnation is mainly ascribed to the fact that the polymer solution can fill the porous mortar and increase the interface adhesion between the new paste and the modified RCA. Note that if the concentration of the PVA solution is overly high, resulting in the coating of a film that is excessively thick onto the RCA surface [76], which increases the ITZ thickness and weakens the ITZ quality, the performance of the RAC may be adversely affected [85,100]. The combined usage of lime soaking and carbonation can produce superior properties (such as mechanical strength and durability) for RAC because the additional CH forms more calcium carbonate in the adhered mortar to fill pores, resulting in a denser microstructure. Previously published papers [31,36,44,66] showed that the mineral type deposited on the RCA surface and the improved efficiency are dependent on the environmental temperature and Ca^{2+} concentration. However, the question of how these parameters affect the mechanical strengths of RAC has not yet been systematically investigated.

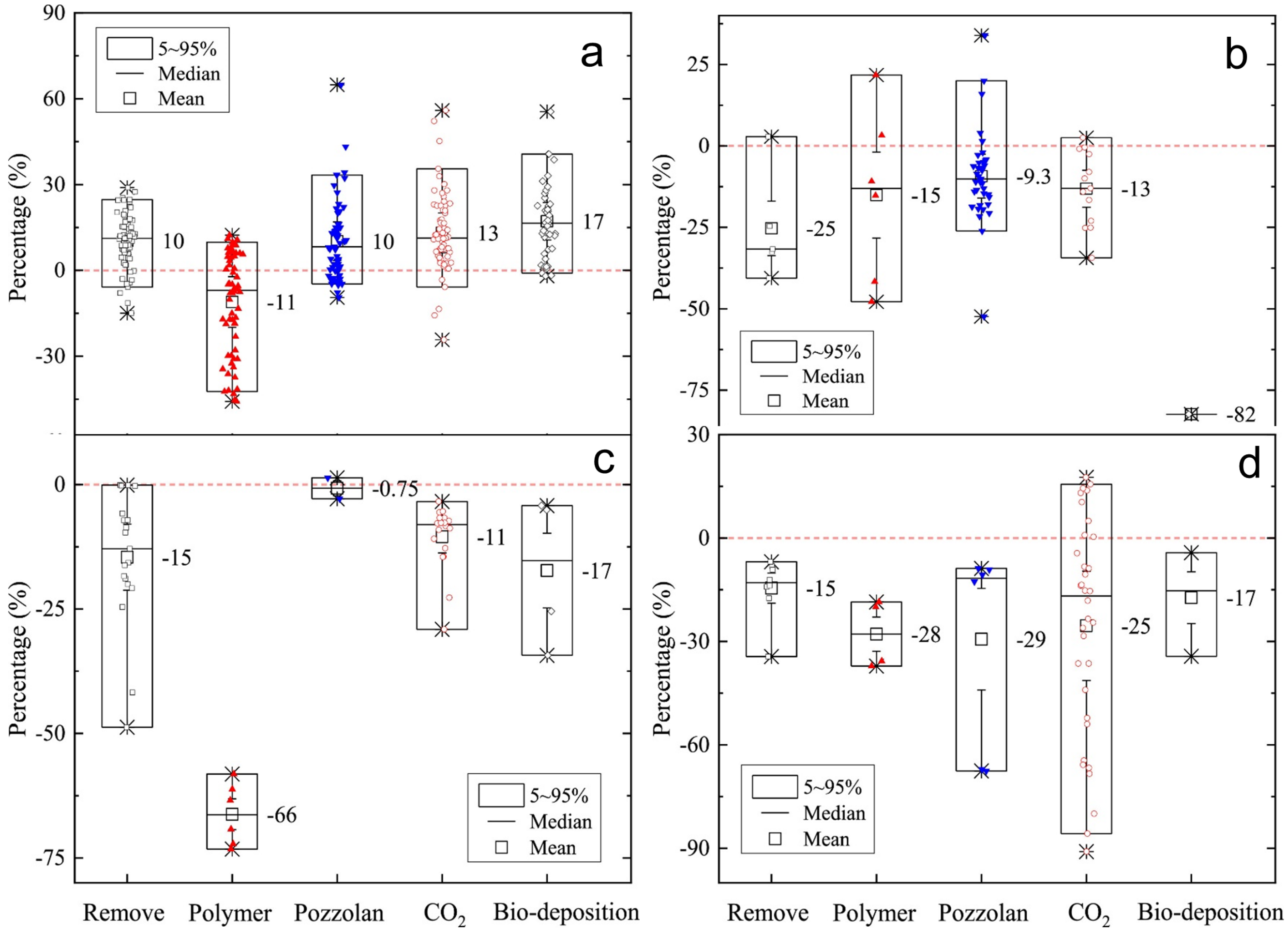

Figure 7. Variation in (**a**) compressive strength, (**b**) shrinkage, (**c**) water absorption and permeability, and (**d**) chloride-penetration resistance of RAC using various pretreatment approaches [6]. Removal is mechanical milling method.

3.2.3. Shrinkage

The characteristics of RAC, such as loose and porous old mortar and high water absorption, lead to its shrinkage, mainly in the form of drying shrinkage, as shown in Figure 7b [101,102]. The removal of old adhered mortar from RCA surfaces can reduce the shrinkage of concrete. For instance, Ismail et al. [28] suggested that the pretreatment of RCA with 0.5 mol/L HCl can remove old adhered mortar from RCA surfaces, resulting in uniform surfaces. Thus, the treatment of RCA can reduce drying shrinkage by 26% at 180 days. Kou and Poon [27] showed that the use of PVA-treated RCA leads to a 15% decrease in concrete shrinkage over 28 days, mainly due to the PVA emulsion filling the adhered mortar on the RCA. In addition, the optimal pretreatment of RCA can be obtained by adjusting the slurry type. The treatment of RAC with pozzolanic material is also an effective approach to reducing concrete shrinkage. Bio-deposition is another promising approach for RCA enhancement, which can fill the porous adhering mortar by producing $CaCO_3$ through special bacteria.

3.2.4. Water Absorption and Permeability

Microcracks in cement concrete provide pathways for the transportation of water molecules or erosion media [103–106]. Therefore, the addition of surface defects to RCA can increase its water absorption and resistance to gas penetration [107].

Typically, higher levels of RCA replacement result in higher permeability of the RAC. As the amount of treated-RCA replacement increases, the permeability gradually decreases, as the disadvantages of RCA are addressed by the removal of the old adhered mortar, as shown in Figure 7c. The polymer pretreatment of RCA can also reduce the water absorption of concrete. The mechanism of the reduction in permeability is related to the depth of the polymer penetration [108,109]. The carbonation treatment of RCA is another approach to improving the permeability of RAC. The main factors governing the modification efficiency of RCA include the strength of the parent concrete, the carbonation curing conditions, and the level of RCA replacement [62,63,70]. Increases in the carbonation curing pressure are beneficial for reducing RCA's water absorption and permeability [107]. For example, the use of bio-deposition-treated RCA can reduce the water absorption of cement composites by approximately 30%, compared to samples made with virgin RCA [57]. According to previously published results [6,7,110], the use of pretreated RCA can improve the chloride-ion-permeability resistance of RAC, as shown in Figure 7d. Kou and Poon [27] found that the use of polymer impregnation to treat RCA can reduce the chloride permeability of RAC by approximately 30%.

4. Effectiveness, Cost, and Environment Analysis of Different Treatment Approaches

Although the pretreatment of RCA can significantly enhance its quality [111–114], there is also the potential risk of damaging the RCA [115–117]. Therefore, this section discusses the effectiveness of different treatment approaches.

Some methods, such as mechanical grinding, the soaking of RCA in acid solution, and heat treatment, were adopted to remove old adhered mortar from RCA surfaces [118–122]. As presented in Table 2, these approaches were shown to be effective in removing the old adhered mortar from the RCA surfaces [123–126]. However, the high cost, the environmental pollution caused by the waste acid solution, and the secondary damage to the RCA due to mechanical collisions, lead to the further optimization of the pretreatment process of RCA [127–129]. The treatment process still needs further optimization in future studies to minimize the damage to RCA.

Table 2. Effectiveness analysis of different treatment approaches [8,23,27,29,30,57,78,79,87,89,130,131].

Performance	Removal	Polymer	Pozzolan	Bio-Deposition	Accelerated Carbonation
Compressive strength	+(9–16)%	-	+(9–16)%	+(9–16)%	≧17%
Flexural and splitting tensile strength	+(0–8)%	+(9–16)%	≧17%	+(9–16)%	≧17%
Elasticity modulus	+(9–16)%	+	+(9–16)%	+(9–16)%	≧17%
Shrinkage	≦−17%	−(8–16)%	−(8–16)%	−(8–16)%	≦−17%
Permeability	−(8–16)%	≦−17%	−(0–8)%	−(8–16)%	−(8–16)%
Chloride-penetration resistance	−(8–16)%	≦−17%	≦−17%	≦−17%	−(8–16)%

Additionally, polymer impregnation, pozzolan slurry, bio-deposition, and accelerated carbonation are used to enhance adhered mortar due to the filling capacity or chemical reactions [32,36,38]. After immersing RCA particles in polymer solution, the formation of polymer films, especially some films with water-repellent properties, may weaken the ITZ region and reduce the performance of concrete [132–135]. According to Figure 8, the pretreatment of RCA through bio-deposition and accelerated carbonation are the two most effective methods for improving the performance of concrete [136–138]. The precipitation of $CaCO_3$ on RCA surfaces with the help of accelerated carbonation or bacteria can reduce RCA's porosity and improve ITZ's quality [139–142]. In particular, accelerated carbonation demonstrates superiority in terms of effectiveness, cost, and environmental effects.

Overall, the bio-deposition and carbonation methods are the two most effective approaches for enhancing the properties of RCA and, thus, improving the performance of concrete [46]. The removal of adhered mortar and bio-deposition are effective strategies to enhance RCA quality and the two best methods to reduce its shrinkage. Polymer impregnation is the most effective way to reduce the water absorption and permeability of RAC [143–147]. However, the use of polymer solutions may reduce the compressive strength of concrete [33,34].

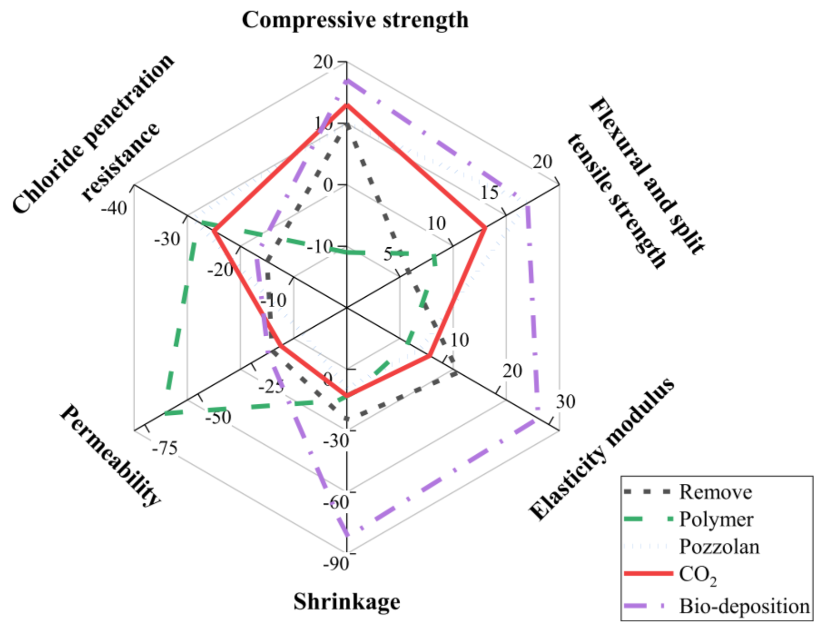

Figure 8. Radar chart of RAC-containing RCA with the assistance of various treatment methods [6].

In addition to treatment efficiency, RCA's treatment cost and environmental impact are important for its wide-scale application [148–150]. The use of RCA as an alternative to NA in the manufacturing of concrete can alleviate the environmental impact of the extraction of NA resources, carbon emissions, and greenhouse-gas emissions [17,34,36–38,151].

It was reported that the production of 1 m^3 of concrete with 100% RCA instead of NA can produce savings of or reductions in mineral resources of about 45% [41,131,148,152]. Inevitably, however, the RCA-pretreatment process adds costs and involves several environmental effects, such as equipment costs, energy consumption, and labor costs [153–157]. For instance, acid-solution treatments, heat treatments, and microwave-removal approaches feature shortcomings [15,28,34], such as environmental pollution, secondary damage to aggregates due to collisions, and high energy consumption. In contrast, accelerated carbonation provides greater environmental benefits. In addition, accelerated carbonization improves the ITZ [158–162]. The cost analysis of biodeposition method is very limited, it requires further studies to promote its potential practical applications.

A universal pretreatment approach for RCA has not existed yet. In this review work, the improved efficiency of various approaches and their impact on the performance of RAC are analyzed and discussed. Decision makers can use appropriate pretreatment methods according to specific conditions to effectively meet practical applications.

5. Case Studies of Application of RCA in Concrete Infrastructure

5.1. Using RCA in Concrete Pavement Layers

According to previous studies [163–166], RCA is directly applied to various pavement layers, such as the surface, subgrade, and base, as well as rigid pavements [167–169]. The replacement of NA with RCA for pavement layers can save limited NA resources, thus decreasing water consumption by about 10%, reducing energy consumption by about 20%, and reducing CO_2 emissions by about 15%, all of which are associated with pavement construction [166–168]. In conclusion, RCA has sufficient mechanical properties to replace virgin aggregates in pavement subgrades, and it is worth promoting and using [163–165]. However, it is essential to note that the direct use of RCA particles in pavement layers is a relatively inefficient approach because their need is very limited, and there is a greater need to broaden or improve the utilization of RCA to promote sustainable concrete.

5.2. The Use of RCA for Sustainable Asphalt Pavements

In addition to its application in pavement layers, RCA has been proposed for asphalt-pavement applications [77,170–173]. The following section describes the latest research progress on the application of RCA in asphalt pavements.

Studies on the effect of the introduction of RCA on the water stability of asphalt mixtures have produced inconsistent results. Typically, the overuse of RCA may not be conducive to the water stability of asphalt pavements [170–172]. Therefore, the use of a higher percentage of RCA (e.g., $\geq$75%) may not be suitable for the manufacturing of asphalt mixtures with outstanding water stability [174–176]. Some approaches have been proposed to apply RCA effectively, such as the coating of RCA with different cementitious pastes or polymer solutions [173–176]. For example, the coating of RCA with a cementitious slurry can improve the water stability of asphalt concrete by approximately 7% [177]. The findings of this study further suggested that RCA enhancement is a suitable path to the enhancement of the water ability of asphalt concrete containing RCA [87,177,178]. Usually, the employment of RCA can enhance the moisture resistance of asphalt concrete in terms of permanent deformation [87,178]. However, this is related to many factors, such as the gradation of the mix, the aggregate shape, and the quality of the RCA. Therefore, for the design of high-performance RCA–asphalt pavements, RCA's overall properties from different sources must be considered [87,174]. The low-temperature crack resistance is a crucial index to determine whether RCA–asphalt concrete is suitable for cold environments [87,172]. In general, increases in the RCA replacement ratio are not beneficial for the low-temperature resistance of RCA–asphalt concrete [87,176]. The use of 45% RCA, or higher, is acceptable for the climatic conditions of Central Europe. However, this is still an important issue that deserves detailed investigation to determine whether RCA–asphalt concrete can exhibit outstanding performance in cold regions [87]. Some key aspects, such as the mix design, RCA dosage, and RCA source, should be considered further in future studies.

5.3. The Use of RCA in Structure Concrete

Furthermore, RCA can also be applied in the construction of some buildings [3,6]. For example, it can be used for lightweight load-bearing superstructural buildings [8,9]. Because of its high porosity and voids, it can be used in applications requiring sound-insulating concrete, such as highway-noise barriers, since materials with many internal voids can effectively absorb sound energy [1,2].

In addition, RAC structures have been extensively used as sustainable structures, primarily because of some of their benefits, such as their ability to reduce landfill and the consumption of natural resources [62,63,69,70]. For instance, Xiao et al. [131] studied the carbon footprint of two twin towers, with one made of RAC (Tower A, in Figure 9a) and the other made of ordinary concrete (Tower B, in Figure 9a), and the results showed that the use of RAC as a structural material in high-rise structures, instead of NAC, can reduce the carbon footprint by about 2.175 $\times$ 105 kgCe under the conditions of this particular project, a success story that is important for promoting the development of a sustainable building industry. Elsayed et al. [179] evaluated the flexural performance of RC structures containing RCA, and their experimental results showed that the complete replacement of NA with RCA leads to adverse effects on the ductility of beams. Mathew et al. [30] attempted to replace NCA with 60% treated RCA (RCA pre-soaked in cement and fly-ash slurry) and to study the shear behavior of RC beams. The experimental results showed that RAC can be used in structural concrete in practical applications to reduce carbon footprint. Ren et al. [130] developed a new steel–concrete composite adapter and investigated its compressive behavior experimentally and numerically, and the superiority of the steel–concrete composite adapter over RCA was demonstrated.

Figure 9. (**a**) Profile of the project-demonstration buildings and construction of the RAC structure [131]; (**b**) AACW disposal procedure for recycling utilization [171]; (**c**) mock-up RAC specimens [79]; and (**d**) test setup and instrumentation layout of RAC concrete [79].

In general, RCA is underutilized in most developing countries. Typically, RCA is used in sidewalk construction and other low-level applications. Based on experiments and research results, about 40% RCA, or less, is feasible in new construction concrete. Further research can be conducted on pretreatment techniques and modification strategies to use a higher replacement of RCA in RAC.

6. Conclusions and Perspectives

This review provides a comprehensive discussion of the pretreatment of RCA and its impact on the performance of RAC. Furthermore, some case studies of RCA applications in concrete infrastructures are introduced, and the remaining challenges for future work are discussed. Based on our findings, the following conclusions and outlook can be formulated:

(1) The removal of adhered mortar from RCA surfaces and accelerated carbonation with the help of lime water are more effective approaches to enhancing the quality of RCA compared to untreated RCA. More importantly, the acceleration of the carbonization process can consume large amounts of CO_2 gas, thus reducing the greenhouse effect, which has considerable environmental benefits and economic advantages. Furthermore, the introduction of silica–cement nanocomposites is beneficial for enhancing the properties of RCA. Despite the high efficiency of the bio-deposition method in improving the quality of RCA, however, the mechanism behind it needs to be explored and proven in the future, to provide an in-depth understanding of the advantages and mechanisms of bio-deposition reinforcement, thus increasing the practical applications of RCA.

(2) The complex sources of RCA from different concrete structures resulted in huge differences in the quality of RCA, and the effects of different pretreatment approaches fluctuate considerably. Therefore, the quality of RCA varies greatly and lacks the fixed indicators required by standards or specifications. Relevant treatment procedures

should be designed in a targeted manner to obtain maximum efficiency and minimum energy consumption to obtain RCA and RAC with the most stable properties possible.

(3) The effect of treated RCA on the performance of RAC is complicated and closely related to parameters such as the properties of the parent concrete, the pretreatment process, and the amount of RCA used. Although the use of RAC has significant environmental and economic benefits, the additional costs incurred by the enhanced treatment of recycled aggregates need to be considered in future studies. In addition, the long-term strength and durability performance of recycled aggregate concrete in relation to microstructures (e.g., porosity and micro-mechanical characteristics of multiple interfacial transition zones) still need further investigation.

(4) The adverse effects of the application of RCA on the performance of concrete can be mitigated by methods for pre-treating RCA, such as the use of supplementary cementitious materials or carbon nanomaterials. The application of pre-treated RCA can improve the mechanical strength and durability of concrete, which could translate into economic and sustainability benefits. Future research should develop reliable-service-life models that quantify the benefits of using pre-treated RCA in the development of new concrete, and then conduct life-cycle assessments (LCAs) to quantify the reductions in the use of energy and other resources, emissions, and waste during the life cycle of the RAC.

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