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Review

A Review: Strengthening Techniques for Recycled Aggregates

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Abstract

Due to its relatively low apparent density, as well as high water absorption and crushing value, recycled aggregate (RA) is difficult to directly apply in practical concrete production. Existing studies have proposed a variety of pretreatment methods for RA. To further deepen the understanding of their effectiveness in improving the properties of RA and to provide guidance for its practical application, a comprehensive investigation is necessary. The pretreatment methods of RA can be classified into three main categories: physical strengthening, chemical enhancement, and bio-deposition. In this study, physical strengthening includes mechanical grinding and microwave heating, chemical strengthening includes acid treatment, polymer treatment, and carbonation curing, and biological strengthening refers to biological strengthening techniques. Different strengthening methods improve the properties of RA and the corresponding recycled aggregate concrete (RAC) to varying degrees. However, it is essential to control the external treatment conditions appropriately during the strengthening process. In addition, the source of RA and its inherent physical characteristics also have a significant influence on the treatment outcomes. Therefore, the optimal strengthening conditions should be determined based on the specific properties of each type of RA. This study systematically summarizes and discusses the influencing factors associated with each strengthening method, and the discussion section compares the pros and cons from different perspectives. Furthermore, within the context of engineering decision-making for sustainable and durable construction materials, the study also addresses the limitations of current strengthening technologies and proposes potential directions for future research.

Keywords: recycled aggregate; recycled aggregate concrete; recycled mortar; physical strengthening; chemical enhancement; biological strengthening

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1. Introduction

The rapid urbanization and urban renewal in China have led to the demolition of extensive aging infrastructure, generating a substantial volume of construction and demolition (C&D) waste annually. However, there is still no effective method to completely dispose of or recycle such a large volume of waste. In order to mitigate the environmental pollution caused by waste concrete and to make efficient use of these discarded materials, incorporating C&D waste into practical engineering applications for resource reuse is of great significance. According to existing statistics [1], approximately 30% of construction and demolition waste consists of discarded concrete. Therefore, the recycling and reuse of waste concrete have become a research focus among scholars both in China and abroad.

Recycled aggregate concrete (RAC) technology is considered one of the most efficient and direct approaches to addressing the aforementioned issues. RAC refers to concrete in which waste concrete is crushed, screened, and cleaned, and the natural aggregates (NAs) are partially or completely replaced with recycled aggregate (RA). After the crushing and screening process, RAs are generally classified by particle size into RCA and recycled fine aggregate (RFA). Aggregates with a particle size greater than 4.75 mm are defined as RCA, while those smaller than 4.75 mm are classified as RFA [2]. The detailed interfacial structure of RAC can be described as follows [2,3]: the old interfacial transition zone (old ITZ) refers to the interface between the original NA and the adhered porous hardened cement mortar within the RA, new ITZ_1 represents the interfacial zone formed between the NA and the newly mixed cement mortar, ITZ_2 is the newly formed interface between the hardened porous mortar attached to the RA and the fresh cement mortar, and new ITZ_3 corresponds to the interface between the original NA within the RA and the newly mixed cement mortar. The coexistence of these multiple ITZs is one of the main factors responsible for the inferior mechanical and durability properties of RA and RAC compared with natural aggregate (NA) and natural aggregate concrete (NAC) of the same mix proportion.

From the perspective of physical properties, RA exhibits a more irregular particle shape and a rougher surface due to the presence of a large amount of adhered mortar (AM). RA generally consists of NA coated with a layer of AM, and an interfacial transition zone (ITZ) is formed between them, which contains numerous pores and microcracks [4]. This microstructural feature is one of the main reasons for the higher water absorption, greater porosity, and lower crushing strength observed in RA [5–8]. From a chemical perspective, the surface of RA is covered with a considerable amount of AM, which contains various cement hydration products such as calcium silicate hydrate (C–S–H), calcium hydroxide (CH), and ettringite (AFt) [9]. In contrast, NA is mainly composed of calcium carbonate and silicon dioxide. Therefore, notable differences exist between RA and NA in terms of their chemical composition and properties. In addition, the surface of RA not only exhibits a complex physical morphology but, more importantly, is enriched with CH, which alters the hydration pathway of the new cement paste. This unique interfacial induction effect hinders the stable nucleation of high-strength C–S–H gels and instead promotes further formation of CH. As a result, a weak and calcium-rich phase tends to develop within the interfacial zone, thereby deteriorating the overall performance of the concrete [10].

According to existing studies [2], the commonly adopted approaches to enhance the properties of RA can be categorized into two main strategies: removing the AM and strengthening the AM itself. Based on a comprehensive summary of various treatment methods, these enhancement strategies can be further classified into three major types: physical strengthening, chemical enhancement, and biological strengthening [11,12]. Physical strengthening methods mainly include mechanical treatment [13–15] and microwave heating [10], chemical enhancement methods involve acid solution treatment [16,17], polymer modification [18], and carbonation curing [19,20], while biological strengthening is typically achieved through bio-deposition techniques [21,22]. Mechanical grinding, microwave heating, and acid solution treatment are the most commonly used methods for removing the AM from the surface of RA. These techniques have been proven effective in significantly reducing or even completely eliminating the AM layer [23]. In contrast, polymer modification, carbonation curing, and bio-deposition methods mainly function by improving the weak zones of RA that arise from insufficient filling capacity or unfavorable chemical reactions [24]. In the polymer coating method, polyvinyl alcohol (PVA) is generally preferred over silane-based polymers. This is because the application of polymer emulsion on the surface of RA can effectively reduce its porosity, while the hydrophobic film formed by the reaction between silane-based polymers and C–S–H hinders the

bonding between the RA and the new cement paste [25]. Carbonation curing has been proven to effectively improve the properties of RCA and is considered a highly promising technique due to its technical, environmental, and economic advantages [26]. In contrast, the bio-deposition technique can generate calcium carbonate ($CaCO_3$) on the surface of RA, effectively filling or narrowing surface cracks. The calcium carbonate-based products formed through this process exhibit excellent micromechanical properties. However, the testing conditions for bio-deposition are rather stringent and difficult to control [27].

Beyond the above strengthening strategies, further modification routes have been investigated: electropulse heating (EPH) to thermally disrupt weak interfacial phases and cleanse the RA surface [28–31], nano-silica (nano-SiO_2) treatment to provide nucleation sites and pore filling for matrix densification [32–34], and impregnation with volcanic ash-based pozzolanic slurries to promote secondary reactions and refine the interfacial microstructure [35–38]. In addition to modifying the aggregates to facilitate the reuse of waste concrete, the overall performance of RAC can be enhanced by incorporating fibers [39]. Representative systems include basalt fiber-reinforced RAC [40], steel fiber-reinforced RAC [41,42], and hybrid steel–polypropylene fiber-reinforced RAC [43]. Moreover, synergistic strategies that combine aggregate modification with fiber incorporation have also been reported to further improve the mechanical and durability properties of RAC [44].

In summary, adopting appropriate strengthening strategies can effectively enhance the properties of both RA and RAC. However, the existing literature is still fragmented, and a unified taxonomy for organizing the major strengthening routes and synthesizing the key findings is lacking. This study critically reviews the current research on aggregate-strengthening methods, including: mechanical strengthening, microwave heating, acid solution treatment, polymer modification, carbonation curing, and bio-deposition. The advantages, limitations, and critical influencing factors associated with each technique are systematically analyzed and compared to highlight their strengths and weaknesses in the context of sustainable concrete production. The objective is to provide a comprehensive reference for further improvement in RA quality, guide engineering decision-making, and inform practical applications in the field of durable and eco-friendly construction.

2. Literature Sources and Selection Strategy

This review aims to systematically synthesize research progress on strengthening technologies for recycled aggregates (RAs). Given the diversity of technical routes, the multi-scale nature of research scenarios, and the dispersion of frontier findings across journals from different disciplines and regional literature, a theme-driven narrative review approach was adopted for literature collection and screening, aiming to ensure broad coverage while minimizing potential selection bias.

2.1. Data Sources, Time Window, and Document Types

The literature in this review was mainly sourced from Scopus, Google Scholar, and CNKI. Specifically, Scopus was used to retrieve peer-reviewed articles from mainstream international journals; Google Scholar was used for supplementary searches and citation tracking to identify studies that may not be fully covered by a single indexing database; and CNKI was used to include a small number of Chinese journal papers and relevant theses/dissertations to improve content coverage. Full texts were primarily accessed through publisher platforms and academic repositories (e.g., ScienceDirect, SpringerLink, MDPI, ASCE Library, and IOPscience).

The formal time window of interest was set to 2010–2025 to reflect the main development stage of recycled aggregate (RA) and recycled aggregate concrete (RAC) strengthening technologies. Studies published within this period constitute the majority of the references

(approximately 95%), while a limited number of pre-2010 publications were retained mainly for fundamental background and mechanistic explanations and were not used as core evidence for the main conclusions. Regarding document types, this review primarily considered peer-reviewed English-language journal articles, supplemented by a small number of Chinese journal papers and a very limited number of theses and dissertations.

2.2. Keyword Framework and Screening Strategy

Around the core theme of "the effects of RA strengthening technologies on the performance of RA and RAC", a keyword framework was established to cover material targets, strengthening routes, and performance indicators. The corresponding keywords included recycled aggregate, recycled concrete aggregate, RAC, recycled mortar, physical/mechanical treatment, microwave treatment, acid treatment, polymer modification, carbonation/CO_2 curing, bio-deposition, and MICP. During the search and screening process, keywords were combined in the form of "target (RA/RAC) + strengthening method + performance indicators (mechanical properties/microstructure)" to cover major strengthening routes and key evaluation dimensions.

As this study adopts a theme-driven narrative review strategy, the literature set was progressively developed through "database searching + citation tracking (snowballing) + iterative updating". During screening, priority was given to studies that are directly relevant to RA and RAC strengthening, providing clear descriptions of methods and parameters, reporting quantifiable results, and coming from reliable sources, while maintaining balanced coverage across different strengthening routes as much as possible. It should be noted that narrative reviews may still involve a degree of selection bias; to mitigate this risk, this review employed multi-database cross-checking, citation tracking, and quality-control considerations to improve coverage and strengthen the robustness of the conclusions.

3. Physical Strengthening

Physical strengthening is a commonly used approach for reducing AM from the RCA surface, which will improve the microstructural characteristics by improving interfacial bonding with the new cement paste.

3.1. Mechanical Strengthening

3.1.1. Overview

Internationally, mechanical strengthening techniques include Japan's vertical eccentric grinding device [45], horizontal rotary grinding method [46], and heat-assisted grinding process [47,48]. The former Soviet Union reported an in-mill grinding method in two basic variants: one with grinding media and the other without [49]. In practice, these approaches are hindered by process complexity, bulky equipment, high energy consumption, and severe equipment wear, which has limited their widespread engineering application [50].

Building on improvements to mechanical strengthening, Li et al. were the first to propose the particle-shaping method [50]. The underlying mechanism is to reprocess low-quality recycled aggregate (RA) obtained from simple crushing. By inducing high-velocity self-collision and friction among the RA particles, the AM or cement paste on their surfaces is detached, and protruding sharp edges are removed. Consequently, the aggregate becomes cleaner and more rounded, which strengthens the RA and improves its compatibility and interfacial bonding with fresh cement paste. The structural principle of the particle-shaping device is shown in Figure 1 [51]. The equipment consists of a main unit, a dust-collection system, an electrical control system, a lubrication system, and a pressure-sealing system. The main unit is equipped with a vertically rotating impeller. During operation, unmodified RCA is fed through the top inlet and divided into two streams:

one portion falls into the impeller cavity and is propelled at high speed by centrifugal force, the other descends along the aggregate distribution system of the main unit and then collides with the aggregate projected by the impeller. In this process, because the high-speed aggregates make minimal contact with the machine wall, the device exhibits lower energy consumption, a longer service life, and greater ease of installation, operation, and maintenance. After treatment, the RA presents a smoother surface, improved particle shape, increased bulk density, and higher purity.

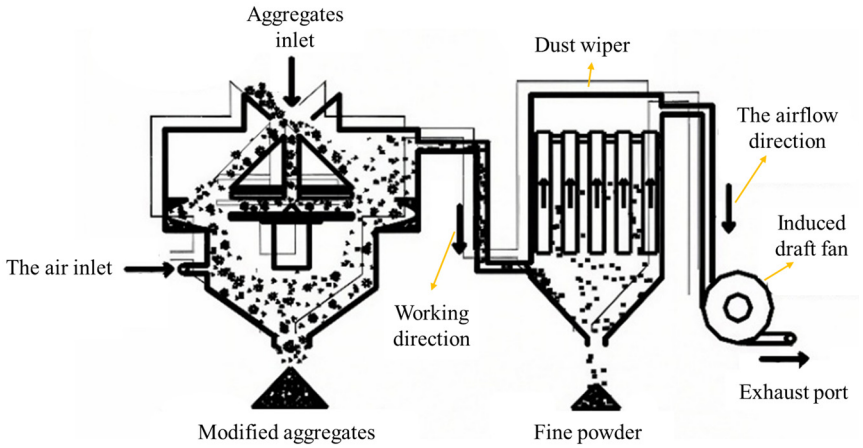


Figure 1. Schematic diagram of the particle-shaping device and its operating principle [51]. Reproduced from Ref. [51] under the CC BY 4.0 license.

3.1.2. Effects of Mechanical Strengthening on RA and RAC

Beyond the above studies, researchers have also employed various grinding devices to treat aggregates and have summarized how different mechanical grinding setups influence RA and RAC performance, for example, a concrete mixer fitted with internal steel balls [52], a rotary drum mixer [53], a jaw crusher [54], and the Los Angeles abrasion machine [55–59]. Some researchers reintroduced RA obtained from simple grinding back into the grinder and, by controlling the machinery and continuously adjusting the grinding system, performed a secondary grinding process [60]. Dilbas et al. used the Los Angeles abrasion machine and systematically varied two key factors: the number of steel balls (ranging from 0 to 12) and the number of rotations (from 100 to 500). Their findings revealed that the optimal combination for enhancing aggregate properties was 10 steel balls and 500 revolutions. This nuanced approach highlighted the importance of precise control over grinding parameters to achieve optimal recycled aggregate concrete (RCA) quality [54]. Pedro et al. took a comparative approach to RCA processing, contrasting simple crushing with a jaw crusher to a more intricate method that involved secondary crushing with a jaw crusher followed by a hammer crusher. Their results indicated that the second crushing process significantly reduced the amount of adhered attached materials (AMs), thereby improving the quality of RCA. This led to the production of RAC with notably superior mechanical properties and durability. These findings suggest that secondary comminution may be a critical factor in optimizing the performance of RAC, providing valuable insights into the processing techniques for producing high-quality RCA [61].

Table 1 summarizes the effects of different mechanical grinding techniques on RA properties. As shown in Table 1, extending the grinding duration and adjusting the number of steel balls and drum revolutions can, to some extent, improve the performance of RA. When RA was treated using a concrete mixer with internal steel balls, aggregate properties improved with increasing grinding time; however, the gain from 12 to 15 min was marginal, indicating 12 min as the optimal treatment time. When RA was processed in a rotary drum

mixer, the enhancement was more pronounced for smaller-size RCA (4.75–9.5 mm) than for larger-size RCA (9.5–19 mm). When RCA was processed using a Los Angeles abrasion machine, heat-assisted grinding, i.e., heating followed by grinding, produced superior improvements compared with grinding alone.

Table 1. Performance changes in RA after different mechanical grinding treatments [52–54,58].

Strengthening Method	Aggregate Type	Untreated RA			Mechanical Treatment		Mechanically Treated RA		
		Apparent Density/ (kg/m^3)	Water Absorption of Aggregate/%	Crush Value/%			Apparent Density/ (kg/m^3)	Water Absorption of Aggregate/%	Crush Value/%
Concrete mixer with built-in steel ball [52]	RMAs (recycled concrete aggregate + recycled brick aggregate)	2406	9.14	23.3	Grinding time (min)	3	2459	8.61	20.3
						5	2460	8.05	18.7
						8	2465	7.90	18.0
						10	2494	7.30	17.2
						12	2512	6.79	16.9
						15	2514	6.73	16.8
Rotary drum mixer [53]	RCA (9.5–19 mm)	2268	4.94	—	Grinding time (min)	10	2358	4.01	—
						15	2328	4.09	—
	RCA (4.75–9.5 mm)	1946	11.94	—	Grinding time (min)	10	2220	6.06	—
						15	2261	5.56	—
Los Angeles rattler [54]	RCA (11.2–22.4 mm)	1800	8.95	-	Number of iron balls + number of rotations	10 iron balls + 500 times	2470	0.84	—
Los Angeles rattler [58]	RCA	—	1.556	36	Grinding time (min)	5	—	0.93	32
					Heating + grinding	Heating at 300 °C for 24 h + grinding.	—	0.78	30

Figure 2 summarizes the influence of RA, after different mechanical grinding treatments, on the 28-day compressive strength of RAC. From Figure 2, different strengthening devices lead to measurable improvements in the mechanical performance of RAC prepared with treated RA. The increases in 28-day compressive strength are 8.8%, 21.5%, 15.3%, and 20.8% for treatments 1–4, respectively. Notably, heating combined with the Los Angeles abrasion machine yields a greater improvement than using the Los Angeles abrasion machine alone.

Although mechanical grinding can rapidly remove old mortar from the surface of RCA, deeper studies have shown that it may introduce new defects, cannot heal microcracks, and offers only limited improvement to the interfacial transition zone (ITZ). In practical applications, it is therefore more often combined with other techniques to further enhance RCA performance [62–64].

3.2. Microwave Heating Method

3.2.1. Overview

Regarding microwave heating, Ong et al. systematically explored the feasibility of applying microwave technology in the concrete recycling process and elucidated its basic operating principles [65]. The underlying mechanism of microwave heating operates through a dual mechanism. Firstly, it generates steep temperature gradients and high thermal stresses within the mortar, notably in the ITZ with the NA. This process partially disintegrates and removes the adhered cement paste [51]. The normal stresses generated at the interface are the primary driver of aggregate–mortar separation. When the induced stresses exceed the tensile strength of the mortar, microcracks initiate at the interface and propagate [66,67]. Second, steam expansion within pores during heating can assist in

removing AM [67]. The general procedure for microwave treatment is as follows: Recycled aggregate (RA) is pre-saturated, then subjected to repeated microwave irradiation and water-quenching cycles, followed by drying and mild mechanical separation to remove adhered AM [68]. The microwave heating process is illustrated in Figure 3.

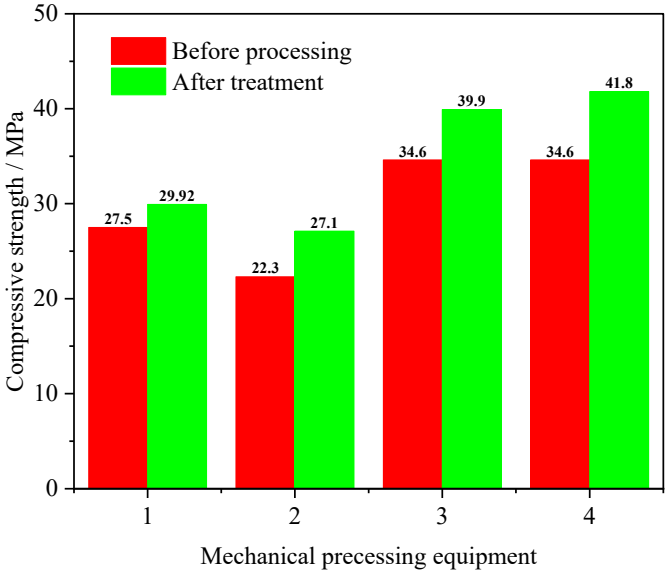


Figure 2. 28-day compressive strength of RAC with RA treated by different mechanical strengthening techniques [52,53,58]. (Mechanical processing equipment for coordinates 1–4: 1—rotary drum mixer [53], 2—concrete mixer with internal steel balls [52], 3—Los Angeles abrasion machine [58], 4—heating combined with a Los Angeles abrasion machine [58]).

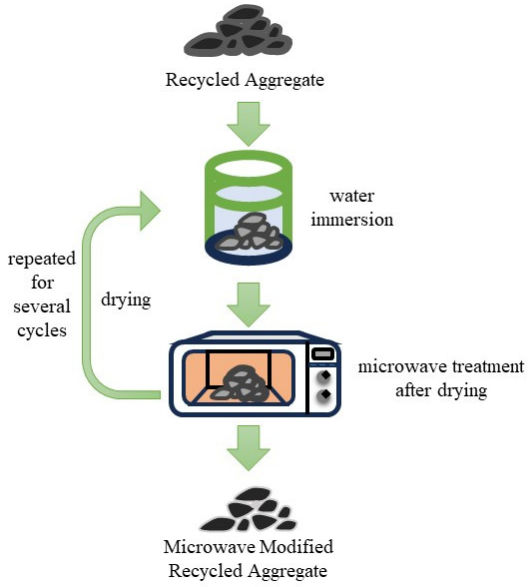


Figure 3. Schematic diagram of the microwave heating process.

Compared with conventional heating, microwave heating requires a lower temperature, less energy, and a shorter duration, thereby mitigating the degradation of RA during processing and reducing potential durability concerns [51]. Moreover, the process generates less CO_2 and yields higher-quality RCA [69]. Xiao et al. examined the microstructural changes induced by microwave treatment and observed that, during heating, C–S–H and AFt in the mortar decompose, while moisture evaporates, leading to increased porosity and a looser structure. As moisture migration and mineral decomposition proceed, the

separation between mortar and aggregate is further promoted [66]. The energy, heat, and moisture transfer mechanisms in concrete under microwave irradiation, as shown in Figure 4, form the basis for moisture migration and microstructural loosening [70].

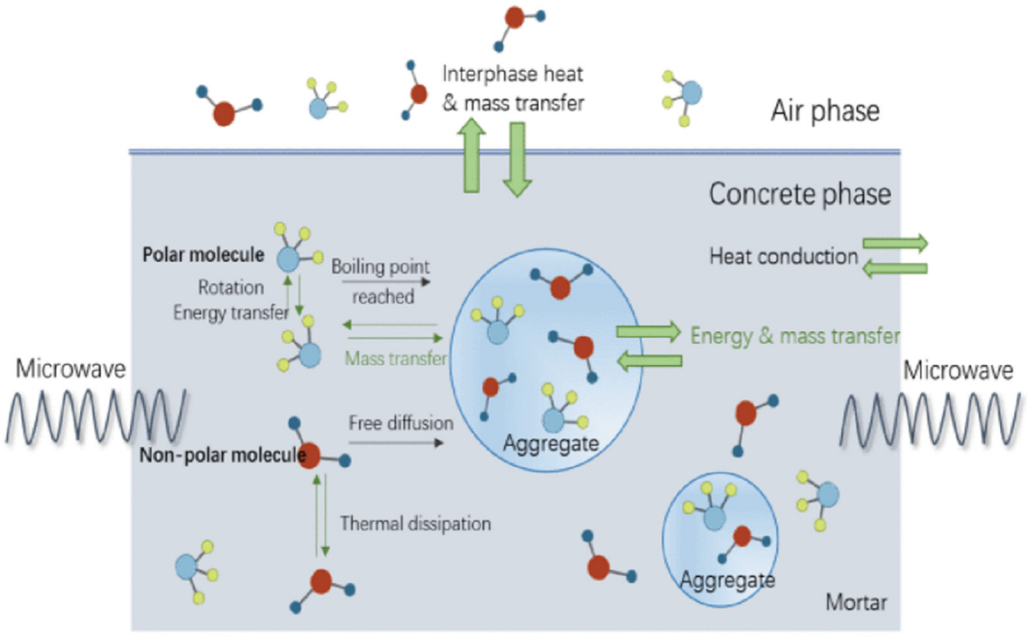


Figure 4. Mechanisms of energy, heat, and moisture transfer in concrete under microwave irradiation [70]. Reproduced from Ref. [70] under the CC BY 4.0 license.

Microwave pretreatment can effectively reduce fracture energy and increase the degree of aggregate liberation. Notably, its effect is more pronounced for coarse aggregate than for fine aggregate, because the ITZ around coarse particles is thicker and more vulnerable, leading to easier separation. Experimental studies further indicate that concrete produced with microwave-treated RA exhibits significantly improved mechanical properties, including higher compressive and flexural strengths and an increased elastic modulus [71].

3.2.2. Effects of Microwave Heating on RA and RAC

Regarding the influence of microwave power on aggregate and concrete performance, Akbarnezhad et al. investigated the effects of high-power microwave treatment (10 kW) on water-saturated recycled concrete aggregates (RCAs) [72]. Their findings demonstrated that microwaves were highly effective in removing the mortar adhered to the surface of RCA, suggesting that microwave treatment could be a promising method to improve RA quality by facilitating the separation of mortar from aggregates. In contrast, Xiao et al. adopted a low-power microwave protocol, subjecting water-saturated RCA to 800 W irradiation in 5 min cycles, followed by cold-water treatment [73]. The treatment was repeated for 15 and 20 cycles, respectively. This approach also successfully removed attached mortar, enhancing the quality of RCA. These results suggest that microwave-assisted mortar removal can be achieved under both high-power short-duration exposure and low-power multi-cycle protocols, indicating a relatively broad processing window for improving RCA quality.

Further investigations have expanded the range of microwave power treatments. For example, Chen et al. explored various power levels, heating RCA at 2 kW, 3 kW, 4 kW, and 5 kW for exposure times of 200, 300, and 400 s [74]. Their results indicated that a 200 s exposure time yielded the best results, regardless of the power level, suggesting that there may be an optimal exposure time for maximizing the effectiveness of microwave treatment. This finding contrasts with Zhao et al., who applied 1600 W microwaves in 4 min cycles

followed by cold-water treatment, repeating the cycle 5 and 15 times [75]. Zhao et al.'s results further underscore the importance of treatment duration and cycle repetition in improving the performance of RCA.

These studies collectively illustrate the potential of microwave treatment as a versatile technique for enhancing RCA quality. While the power level plays a significant role, factors such as exposure time, treatment cycles, and post-treatment procedures (e.g., cold-water treatment) also contribute to the overall effectiveness of the method. The comparison of different protocols provides valuable insights into the optimization of microwave treatment for RA processing, suggesting avenues for future research to fine-tune these parameters for even greater improvements in concrete performance.

Table 2 summarizes the effects of different microwave-heating setups on the treatment performance of RA. As shown in Table 2, the properties of RA are strongly influenced by microwave power, per-cycle irradiation time, and the number of cycles, and they are generally positively correlated with these parameters. In the tests by Chen et al., the water absorption and crushing value of the aggregates increased after microwave treatment (except at 2 kW), with the effect being more pronounced at higher powers (4–5 kW). At 2 kW, the aggregate properties were comparable to those of NA [74], likely because lower-temperature heating promoted densification and thus enhanced certain physical attributes. Moreover, both Xiao et al. and Zhao et al. observed that the improvement in aggregate performance was positively correlated with the number of microwave cycles [73,75].

Table 2. Effects of different microwave heating equipment on the performance of RA [72,73,75].

Microwave Equipment	Microwave Power/w	Untreated RA				Microwave Processing Conditions	Microwave-Treated RA			
		Apparent Density/ (kg/m^3)	Water Absorption of Aggregate/%	Crush Value/%	Mortar Content/%		Apparent Density/ (kg/m^3)	Water Absorption of Aggregate/%	Crush Value/%	Mortar Content/%
Pilot-scale microwave processing system [72]	10,000	2370	4.2	47	—	1 min microwave	2460	2.8	24	—
Microwave oven [73]	800	2478	6.7	14.1	20	5 min microwave (15 cycles)	2588	4.8	9.8	13.1
						5 min microwave (20 cycles)	2596	4.5	10.2	11.2
Microwave vacuum high temperature furnace [75]	1600	2332	7.9	37	23.6	4 min microwave (5 cycles)	2378	5.4	15.4	20.3
						4 min microwave (20 cycles)	2547	1.8	6.5	4.8

Figure 5 summarizes the 28-day compressive strength of RAC produced with RA after different microwave treatments. From Figure 5, relative to RAC made with untreated RA, the 28-day compressive strength increases by 42.59%, 9.39%, and 10.36% for treatments 1–3, respectively. Thus, microwave pretreatment of RA delivers a marked enhancement in the 28-day strength of RAC. Moreover, the resultant strength approaches that of NAC, with only a small residual gap. A plausible reason why the performance still falls short of NAC is that, after microwave pretreatment, RCA may retain residual thermal stresses and pore-pressure effects relative to NA [76]. Moreover, analysis of different microwave cycle counts shows that, within a certain range, increasing the number of cycles leads to greater improvements in the 28-day compressive strength of RAC.

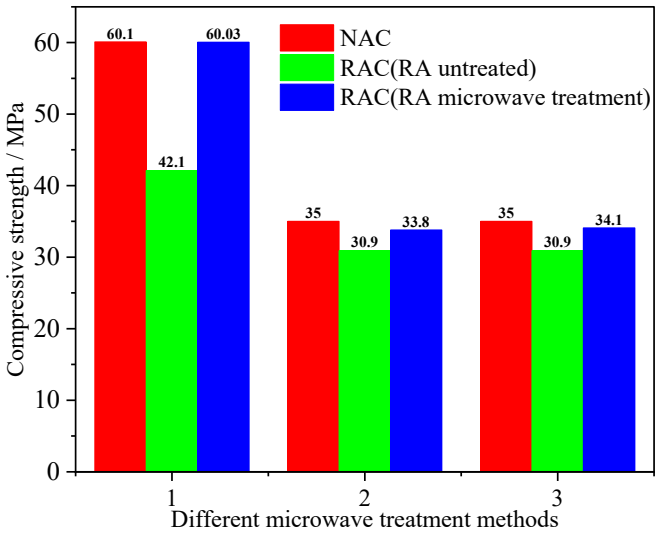


Figure 5. Effect of different microwave heating techniques on the 28-day compressive strength of RAC [72,73]. (Different microwave treatment methods for coordinates 1–3: 1—pilot-scale microwave system, 1 min exposure [72], 2—microwave oven, 5 min irradiation per cycle, 15 cycles [73], 3—microwave oven, 5 min irradiation per cycle, 20 cycles [73]).

Additionally, Zhao et al. reported that water immersion cooling after microwave irradiation improves the removal efficiency of organic matter [75]. Goliya et al. found that microwave heating renders the RA surface smoother, with most pits and microcracks healed, thereby reducing the extent of the interfacial transition zone (ITZ) in recycled aggregate concrete (RAC) [57].

Microwave heating can significantly improve the water absorption, apparent density, and crushing value of RA, while offering lower carbon emissions and energy savings. In addition, low-power microwave treatments are safer and more efficient, effectively minimizing thermal damage to the parent aggregates. It should be noted that, because concrete is a complex artificial composite, its response to microwave irradiation is highly sensitive to factors such as mix proportion and moisture content, yet the underlying theoretical understanding remains limited [51]. Consequently, microwave technology has not yet been implemented on a large scale in civil engineering practice.

3.3. Summary

Both mechanical grinding and microwave heating can improve RA, but their relative advantages depend on RA characteristics and practical constraints. Mechanical grinding is generally preferable when a simple, scalable, and low-risk process is required. Microwave heating may be more suitable for RA with a high content of adhered mortar where interfacial weakening is desired, provided that heating parameters are carefully controlled to avoid unintended damage. In practice, a combined route (e.g., microwave preheating followed by mild grinding or washing) can offer a balanced approach by promoting debonding and then physically removing the weakened mortar. For engineering selection, the cost-effectiveness should be evaluated against a unified performance target—for example, improvements in key RA indicators per unit cost, energy input, and processing time.

4. Chemical Strengthening

Chemical strengthening operates by employing chemical reagents to react with recycled aggregate (RA), thereby removing AM or filling surface microcracks and pores to achieve reinforcement.

4.1. Acid Solution Treatment

4.1.1. Overview

Acid solution treatment is a commonly used approach for removing AM, wherein the acid reacts with the cementitious matrix and dissolves hydration products, thereby detaching or thinning the AM layer [77]. Frequently reported solutions include hydrochloric acid (HCl), sulfuric acid (H_2SO_4), nitric acid (HNO_3), phosphoric acid (H_3PO_4), and, in some studies, salt solutions such as Na_2SO_4 [23,77]. Because strong acids (e.g., HCl, H_2SO_4) introduce potentially harmful ions (Cl^-/SO_4^{2-}) that may adversely affect RCA, and because the spent solutions are difficult to treat, careful selection of reagent type, concentration, and post-treatment neutralization are required.

Wang et al. therefore introduced an acetic acid soaking method for RCA, which not only removes AM effectively but is also more environmentally friendly, economical, and safe [78]. The principal chemical reactions involved in acid treatment are summarized in Equations (1)–(4) [77].

$$Ca(OH)_2 + 2H^+ \rightarrow Ca^{2+} + 2H_2O \quad (1)$$

$$CaO + 2H^+ \rightarrow Ca^{2+} + H_2O \quad (2)$$

$$Fe_2O_3 + 6H^+ \rightarrow 2Fe^{3+} + 3H_2O \quad (3)$$

$$Al_2O_3 + 6H^+ \rightarrow 2Al^{3+} + 3H_2O \quad (4)$$

Studies indicate that different acids exhibit different efficiencies in removing mortar. H_2SO_4-treated RA and the resulting recycled aggregate concrete (RAC) generally outperform those treated with HCl, HNO_3, or H_3PO_4 [58,77]. Saravanakumar et al. compared SEM images acquired before and after acid treatment and found that the treatment significantly alters the surface micro-morphology and the amount of residual attached mortar (AM) [79]. Specifically, H_2SO_4 achieved the most effective AM removal; HNO_3 also removed AM efficiently but left slightly more residue than H_2SO_4; in contrast, HCl-treated aggregates still exhibited substantial AM remnants and pronounced surface porosity, indicating a weaker effect than the H_2SO_4 and HNO_3 treatments. However, Kim et al. reported contrary findings: sulfate attack during H_2SO_4 treatment generates gypsum ($CaSO_4 \cdot 2H_2O$), which can subsequently react with cement aluminates to form AFt, thereby degrading strength [80]. Consequently, compared with H_2SO_4, HCl treatment was found to yield better RAC performance, and this outcome has been independently corroborated [81]. A plausible explanation is that immersing RFA in sulfuric acid promotes gypsum formation; if residual gypsum on the washed aggregate surface is not completely removed, it can react with calcium aluminates in the cement to produce needle-like AFt, increasing internal voids and compromising the matrix–aggregate interface [82,83].

Factors influencing AM removal efficiency during acid treatment include acid concentration and soaking time. Low-concentration solutions tend to yield a cleaner, more uniform RCA surface, whereas high-concentration acids can damage the surface, making the aggregate more brittle and porous [2]. When RCA was treated with 0.8 mol/L HCl, the improvement in concrete strength was markedly lower than that achieved with 0.1 mol/L or 0.5 mol/L solutions, likely due to surface embrittlement that undermines the stability of strength gains [84].

When RCA was treated with a 5% acetic acid solution, adverse effects on the aggregate were observed compared with 1% and 3%, leading to reduced concrete strength [78]. In addition, appropriately extending the acid soaking time facilitates the removal of loose AM, which is beneficial for increasing RAC strength, and the optimal duration depends on the acid type employed [23].

4.1.2. Effects of Acid Treatment on RA and RAC

Several studies have explored the impact of acid treatment on the performance of RCA and RAC, with varying acid concentrations, exposure times, and acids used. Pandurangan et al. soaked RCA in 0.1 M HNO_3 for one day, reporting significant improvements in both the RCA and the resulting RAC [59]. This suggests that a controlled HNO_3 treatment can improve RCA by weakening/removing adhered mortar while limiting undesired damage to the aggregate. Purushothaman et al. investigated acid pre-soaking of RCA using HCl, H_2SO_4, and H_3PO_4 (0.1 M, 24 h) [58]. The results showed that the extent of performance improvement was acid-dependent, indicating that acid type should be selected carefully to target specific RCA properties. Shi et al. summarized that, in acid pre-soaking (0.1 M, 24 h), HCl was the most effective because its reaction products are water-soluble, whereas some products of H_2SO_4 tend to crystallize (and those of H_3PO_4 are unstable) [85]. They also noted that chloride and sulfate contents increased after treatment but remained within specified limits; nevertheless, the potential durability implications (e.g., sulfate-related risks) of using H_2SO_4 should be considered. Wang et al. explored the effects of acetic acid in varying concentrations (1%, 3%, and 5%) and different immersion times (1, 3, and 5 days) [78]. Their study aimed to determine the optimal conditions for acetic acid treatment, which could offer a more environmentally friendly alternative to stronger acids. Tam et al. treated RCA with both HCl, H_2SO_4 and H_3PO_4, evaluating improvements in both RCA and RAC [77]. Their results reinforce the idea that acid treatment can enhance aggregate quality, but the specific acid used plays a crucial role in the magnitude of improvement achieved. Similarly, Kim et al. investigated the effects of HCl and H_2SO_4 at a 1:10 water-to-acid ratio on RFA and recycled mortar (RAM) [80]. Both RFA and RAM showed improvements, while the study emphasized that proper removal/control of reaction residues is necessary for practical application. Ismail et al. examined the impact of varying HCl concentrations (0.1 M, 0.5 M, and 0.8 M) and immersion periods (1, 3, and 7 days) [84]. The results indicate that the treatment effectiveness is concentration-dependent, whereas the soaking duration may not be a determining factor for some properties (e.g., water absorption). Saravanakumar et al. compared the effects of 1-day soaking in HCl, H_2SO_4, and HNO_3 [79]. Their study reinforced the variability in treatment effectiveness, further supporting the need for targeted acid treatments based on the desired outcomes.

Table 3 summarizes the improvement effects of different acid treatments on aggregate properties. The studies reviewed show variations in the effectiveness of the treatments. Saravanakumar et al. found that H_2SO_4 produced the greatest increase in apparent density, while HCl yielded a better crushing value [79]. In contrast, Purushothaman et al. reported that H_2SO_4 outperformed HCl in enhancing aggregate properties [58]. Wang et al. identified 1% acetic acid soaking for 1 day as the optimal condition for improving recycled concrete aggregates (RCA), considering time costs, with a recommendation to choose 1% for 1 day over longer periods [78]. Kim et al. observed broadly comparable effects of H_2SO_4 and HCl [80]. Ismail et al. found that 0.1 M HCl was insufficient for significant improvements, while 0.8 M HCl, although providing the largest gains in physical properties such as lower water absorption, was too aggressive and damaged the aggregate surface [84]. They concluded that 1 day of treatment was too short for a complete reaction, and 7 days provided no additional benefits, with the optimal condition being 0.5 M HCl for 3 days.

Differences in acid treatment outcomes are influenced by several key factors. First, the type of RA affects the acid treatment due to variations in porosity, pore distribution, and attached mortar. The size, surface area, and structural differences between RFA and RCA lead to different acid reactivity, which in turn affects water absorption and uniformity. Post-treatment washing also plays a role in removing residual material and retaining beneficial layers, influencing consistency. Additionally, factors such as the residual salts

and cement chemistry of the original concrete, including mineral composition and pH, impact the aggregate surface and overall performance. External factors, such as acid concentration, temperature, treatment time, and stirring, influence reaction rates and uniformity, further complicating comparisons across studies. In conclusion, these factors interact in complex ways: improper combinations can increase damage, while optimized conditions can minimize negative effects. Most studies focus on single factors, often overlooking the interactions between them, which limits the ability to establish unified treatment guidelines. Future research should prioritize multi-factor experiments to clarify these interactions and resolve discrepancies in outcomes.

Table 3. Effect of different acid solution treatments on RA performance improvement [58,78–80,84].

Acid Solution	Acid Concentration	Untreated RA			Soak Time (d)	Acid-Treated RA		
		Apparent Density/ (kg/m^3)	Water Absorption of Aggregate/%	Crush Value/%		Apparent Density/ (kg/m^3)	Water Absorption of Aggregate/%	Crush Value/%
HCl [84]	0.1 M	2330	4.44	29.15	1	2370	3.99	28.02
					3	2390	3.58	27.39
					7	2320	4.63	28.86
	0.5 M				1	2390	3.67	28.73
					3	2390	3.48	27.95
					7	2380	3.75	28.68
	0.8 M				1	2380	3.83	28.34
					3	2400	3.51	28.14
					7	2370	3.95	28.80
Acetic acid [78]	1%	2560	5.95	—	1	2610	4.94	—
					3	2610	4.90	—
					5	2580	4.95	—
	3%				1	2610	5.06	—
					3	2610	5.14	—
					5	2600	4.99	—
	5%				1	2620	5.05	—
					3	2610	5.26	—
					5	2610	5.41	—
HCl [79]	10%	2470	—	33	1	2490	—	26
HNO_3 [79]	10%				1	2550	—	30
H_2SO_4 [79]	10%				1	2650	—	31
HCl [58]	0.1 M	—	1.56	36	1	—	0.92	33
H_2SO_4 [58]	0.1 M				1	—	0.81	33
HCl [80]	9.1%	2270	6.6	—	2	2350	4.3	—
H_2SO_4 [80]	9.1%				2	2350	4.4	—

Figure 6 summarizes the improvement in the 28-day compressive strength of RAC when RA is treated with different acid solutions. From Figure 6, the increases in 28-day compressive strength are 15.43%, 22.85%, 14.96%, 17.73%, 4.17%, 8.00%, 18.34%, 20.41%, and 27.35% for treatments 1–9, respectively. Based on these data, 0.1 M H_2SO_4 outperforms 0.1 M HCl, 3% acetic acid performs better than 1% and 5%, and 10% H_2SO_4 achieves greater improvement than 10% H_3PO_4 or 10% HCl.

Studies show that the effectiveness of acid pretreatment in enhancing the mechanical performance of RAC is closely tied to the replacement ratio, namely, that each acid treatment has an optimal RCA substitution level. This conclusion was validated by Tam et al. [77], who soaked RCA treated with different acids (HCl, H_2SO_4, H_3NO_4) with various replacement ratios and observed the resulting RAC mechanics. In practice, because acid treatment primarily removes AM, it can be combined with mechanical grinding to achieve more thorough AM removal and further improve aggregate quality [23,86].

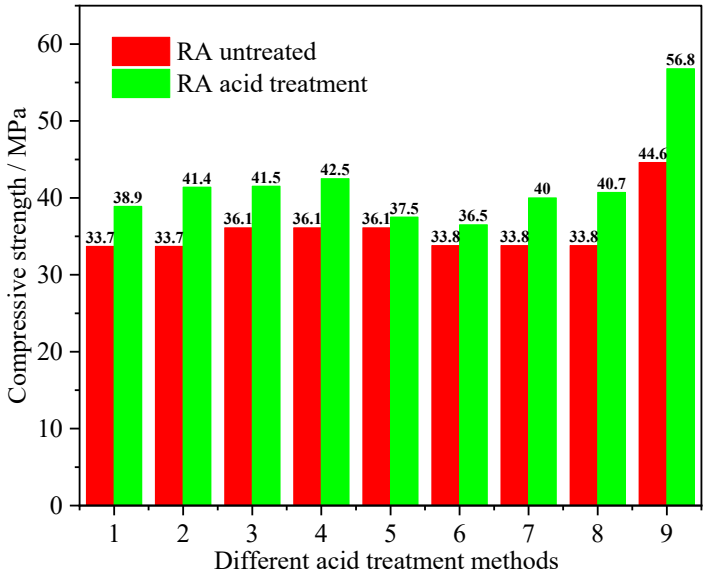


Figure 6. Influence of different acid treatments of RA on the 28-day compressive strength of RAC [58,78,79,84]. (Different acid treatment methods for coordinates 1–9: 1—HCl, 0.1 M, 1 d [58], 2—H_2SO_4, 0.1 M, 1 d [58], 3—acetic acid, 1%, 1 d [78], 4—acetic acid, 3%, 1 d [78], 5—acetic acid, 5%, 1 d [78], 6—HCl, 10%, 1 d [79], 7—HNO_3, 10%, 1 d [79], 8—H_2SO_4, 10%, 1 d [79], 9—HCl, 0.1 M, 1 d [84], RCA replacement ratio: 45%).

4.2. Polymer Treatment

4.2.1. Overview

Polymer treatment enhances the performance of recycled aggregate (RA) and recycled aggregate concrete (RAC) by remedying intrinsic weaknesses of RA and optimizing the interfacial transition zone (ITZ) between aggregate and mortar. When RA is impregnated with a polymer solution, polymer particles diffuse into its pores, voids, and microcracks, and upon coalescence/curing, they seal surface microcracks and thereby reduce porosity. In addition, a polymer film can form on the RA surface, limiting external moisture ingress and consequently lowering water absorption [87]. Moreover, polymer treatment optimizes the aggregate–cement ITZ in two ways: (i) It promotes more complete hydration at the interface, generating a denser assemblage of hydration products that reduces pores and microcracks, and (ii) the polymer film on the aggregate surface bonds more intimately with the hydration products in the fresh mortar, mitigating stress concentration and delaying crack initiation within the ITZ [88].

Figure 7 illustrates the changes in the internal microstructure of RA after PVA modification [89]. As shown in Figure 7, the unmodified RA exhibited abundant internal pores, whereas these pores were markedly reduced after treatment with the PVA solution. This is because, when RC is immersed in the PVA solution, the solution can penetrate the aggregate through surface pores and microcracks; subsequently, the formed PVA film further fills the internal pores. Therefore, PVA solution modification not only seals surface pores and microcracks but also effectively optimizes the internal pore structure of RC.

When the intrinsic properties of RA are improved and the ITZ becomes denser with stronger interfacial bonding, failure of RAC under load is no longer governed by premature aggregate fracture or ITZ cracking. Instead, stresses are transferred more uniformly among the aggregate, the ITZ, and the new mortar, leading to a marked increase in overall load-bearing capacity and, consequently, higher compressive and flexural strengths. Common polymers used to improve RA performance include PVA, silane, and siloxane systems [90]. In general, PVA is considered more effective for aggregate modification than silane-based emulsions [91].

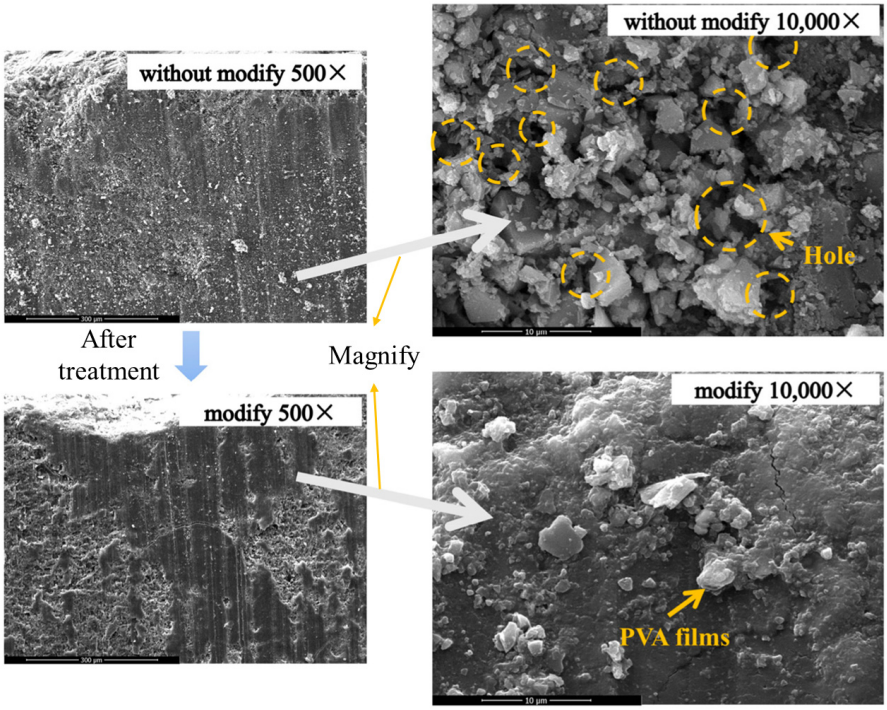


Figure 7. Changes in the internal microstructure of RA after PVA modification [89]. Adapted from Ref. [89] under the CC BY 4.0 license.

Ohama [92] and Su [93] reported that PVA films can alter the flocculation/dispersion state of cement and effectively lower the local water-to-cement ratio at the interface. The presence of a PVA film also retards cement hydration, thereby delaying the initial and final setting times, which may reduce the early compressive strength of RAC [94,95]. However, as time elapses, PVA gradually dissolves in the alkaline environment of concrete, and its adverse influence on the later-age strength development of RAC correspondingly diminishes [24]. It is worth noting that, if the PVA solution concentration is too high, the coating formed on RCA becomes excessively thick and cannot fully dissolve under alkaline conditions, which increases the ITZ thickness, weakens aggregate–paste bonding, and ultimately impairs RA performance [96]. Therefore, the concentration of PVA used to treat RCA must be carefully controlled within an appropriate range.

Moreover, silicon-based waterproofing polymers, such as silane, siloxane, or their combinations, have been demonstrated to be effective enhancement treatments [97,98]. Because siloxane polymer particles are larger than those of silane, silane-based systems penetrate AM more readily than their siloxane counterparts, improving in-depth sealing and interfacial modification. The strengthening mechanism operates through three primary steps. First, silane and siloxane species efficiently penetrate the pore structure of RCA. Second, they undergo hydrolysis within the pores to form silanols, which chemically bond with silanol groups on the silicate-rich aggregate surface. Finally, as moisture evaporates, the silanol groups condense to form a three-dimensional cross-linked siloxane network, thereby sealing defects and stabilizing the interfacial microstructure.

For polymer-based approaches, some researchers have applied silane directly to concrete. Zhu et al. evaluated two silane-based waterproofing strategies: surface coating and integral mixing [99]. The results show that surface coating provides superior improvements in RAC durability (e.g., lower water absorption, slower carbonation, and reduced chloride ingress) with only a minor effect on strength. By contrast, integral mixing can also enhance durability but significantly compromises compressive strength, which must be mitigated by optimizing the water-to-cement ratio or combining with other strengthening measures.

Owing to the relatively high porosity of RAC, silane penetrates more deeply, making the surface treatment particularly effective for protection.

4.2.2. Effects of Polymer Treatment on RA and RAC

Regarding the effects of polymer treatment on RA properties and on the 28-day compressive strength of RAC, Yang et al. enhanced the properties of RCA by spraying a polyvinyl alcohol (PVA) solution onto the aggregate surface, forming a PVA bonding layer [100]. This layer was then wrapped with a cement shell created by an external cement coating, effectively improving the bonding between the aggregate and cement paste. Similarly, Liu et al. immersed recycled aggregate in a 10% silane polymer emulsion (PDMS + MTES) for 24 h and then air-dried it [101]. The silane treatment formed hydrophobic membranes that reduced surface free energy, promoting cement paste redistribution in recycled aggregate-pervious concrete and thereby enhancing strength while maintaining acceptable permeability. Kou et al. explored different concentrations of PVA solutions (6%, 8%, 10%, and 12%) for vacuum impregnation of RCA in both air-dried and oven-dried states [88]. Their findings revealed that a 10% PVA solution was optimal for modifying the aggregate, offering the best balance between enhancing RA properties and maintaining workability.

These treatments suggest that polymer modification, particularly with PVA and silane emulsions, can significantly improve the mechanical properties of RCA and subsequently enhance the compressive strength of RAC. The optimal concentration of polymer solution for modification is a critical factor, as demonstrated by Kou et al.'s work, where a 10% PVA solution provided the best results.

Table 4 presents the improvement effects of PVA and silane emulsions on aggregate properties. As shown in Table 4, although both emulsions strengthen the aggregates, a direct comparison of their performance is not feasible due to the non-uniformity of aggregate particle sizes. For the comparisons by Kou et al. using PVA emulsion on RCA of different sizes (10 mm and 20 mm) and moisture states (air-dried vs. oven-dried), PVA treatment produced a slightly greater density increase for the 20 mm aggregates [88]. It also markedly suppressed the very high water absorption of the 10 mm aggregates. Given that 10 mm RCA typically has poorer initial properties, which is especially reflected in higher water absorption, its absolute improvement after PVA treatment was therefore particularly substantial. In addition, air-dried RCA benefited more than oven-dried RCA, showing greater overall performance gains.

Table 4. Effects of different polymer treatments on the properties of RA [88,90,101].

Polymer Solution	RCA	Untreated RA			Polymer Concentration/%	Polymer Immersed RA		
		Apparent Density/ (kg/m^3)	Water Absorption of Aggregate/%	Crush Value/%		Apparent Density/ (kg/m^3)	Water Absorption of Aggregate/%	Crush Value/%
PVA [101]	4.75–31.5 mm	2470	6.77	16.73	10	2500	6.34	11.80
Silane [90]	5–10 mm	2530	3.75	26	10	2540	2.25	24.1
PVA [88]	10 mm (air-dried)	2356	7.76	—	10	2385	2.38	—
	10 mm (oven-dried)				10	2378	4.32	—
	20 mm (air-dried)	2423	6.23	—	10	2472	1.62	—
	20 mm (oven-dried)				10	2466	2.39	—

Figure 8 shows the improvement in the 28-day compressive strength of RAC using RCA treated with different polymer methods. From Figure 8, the 28-day compressive strength of RAC made with polymer-treated RCA shows an overall upward trend, with strength increases of 22.1%, 22.0%, 41.1%, 65.4%, 84.8%, 1.2%, and 5.6% for treatments 1–7, respectively. As the aggregate-to-cement mass ratio (A/C) increases, the 28-day strength of RAC tends to decrease, but the rate of improvement obtained with 10% silane-treated RCA continues to rise. For 10% PVA-treated RCA, the air-dried aggregates yield higher 28-day compressive strength than the oven-dried ones. In addition, for high-strength RAC made with untreated aggregates, the relative strength gain ratio after polymer treatment is smaller than that of lower-strength RAC made with untreated aggregates.

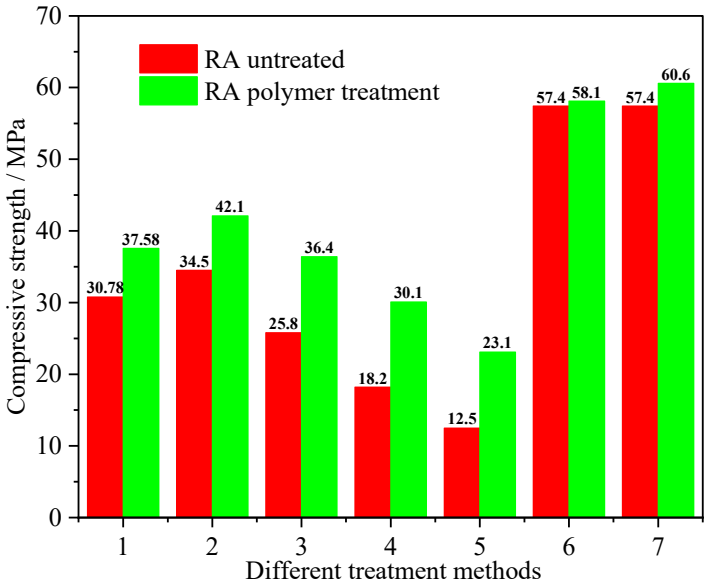


Figure 8. Twenty-eight-day compressive strength of RAC with RA treated by different polymer methods [88,90,101]. (Different polymer treatment methods for coordinates 1–7: 1—PVA solution with an external cement coating [101], 2—10% silane solution, concrete A/C = 2.2 [90], 3—10% silane solution, concrete A/C = 3.0 [90], 4—10% silane solution, concrete A/C = 2.6 [90], 5—10% silane solution, concrete A/C = 3.4 [90], 6—10% PVA treatment on oven-dried aggregates [88], 7—10% PVA treatment on air-dried aggregates [88]).

Additionally, Weng [102] reported that the strength gain of 150 mm × 150 mm × 150 mm cube specimens made with polymer-modified RA was slightly higher than that of 150 mm × 150 mm × 300 mm prisms. In contrast, Xu [92] observed a marginally greater average strength increase in prism specimens than in cubes. These discrepancies may stem from multiple factors (e.g., specimen geometry, size effect, curing uniformity, and stress distribution) and warrant further investigation.

Although polymer treatment can effectively improve the physical properties of RA (e.g., reducing water absorption and refining pore structure), it also presents drawbacks: strong hydrophobicity of silane-based emulsions (which may hinder paste bonding), poor water resistance of PVA, relatively high cost, limited degradability, and potential environmental burdens. Future work should explore hybrid routes, such as polymer–acid or polymer–nanomaterial systems, and develop low-energy process windows to better balance performance, environmental sustainability, and economic viability.

4.3. Carbonation Curing Treatment

4.3.1. Overview

Carbonation curing involves exposing recycled aggregate (RA) to a CO_2-rich environment, where CO_2 reacts with the hardened cement paste and hydration products on the RA surface, such as $Ca(OH)_2$, C–S–H, AFt, and AFm, to form carbonates. The carbonation reactions of these cement hydration products can be represented by Equations (1)–(4) [103]. In addition, unhydrated cement minerals such as tricalcium silicate (C_3S) and dicalcium silicate (C_2S) can also react with CO_2. The carbonation reactions of these unhydrated phases are expressed in Equations (5) and (6) [104]. The formation of $CaCO_3$ during carbonation fills the pores, voids, and microcracks within the RA, thereby improving its compactness and strengthening the new and old ITZ [105,106]. A schematic diagram of the carbonation test is shown in Figure 9 [107].

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O \quad (5)$$

$$C–S–H + CO_2 \rightarrow CaCO_3 + SiO_2 \cdot nH_2O \quad (6)$$

$$3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot 32H_2O + 3CO_2 \rightarrow Al_2O_3 \cdot xH_2O + 3CaCO_3 + 3CaSO_4 \cdot 2H_2O + (26-x)H_2O \quad (7)$$

$$3CaO \cdot Al_2O_3 \cdot CaSO_4 \cdot 18H_2O + 3CO_2 \rightarrow Al_2O_3 \cdot xH_2O + CaSO_4 \cdot 2H_2O + 3CaCO_3 + (16-x)H_2O \quad (8)$$

$$2CaO \cdot SiO_2 + 2CO_2 + nH_2O \rightarrow 2CaCO_3 + SiO_2 \cdot nH_2O \quad (9)$$

$$3CaO \cdot SiO_2 + 3CO_2 + nH_2O \rightarrow 3CaCO_3 + SiO_2 \cdot nH_2O \quad (10)$$

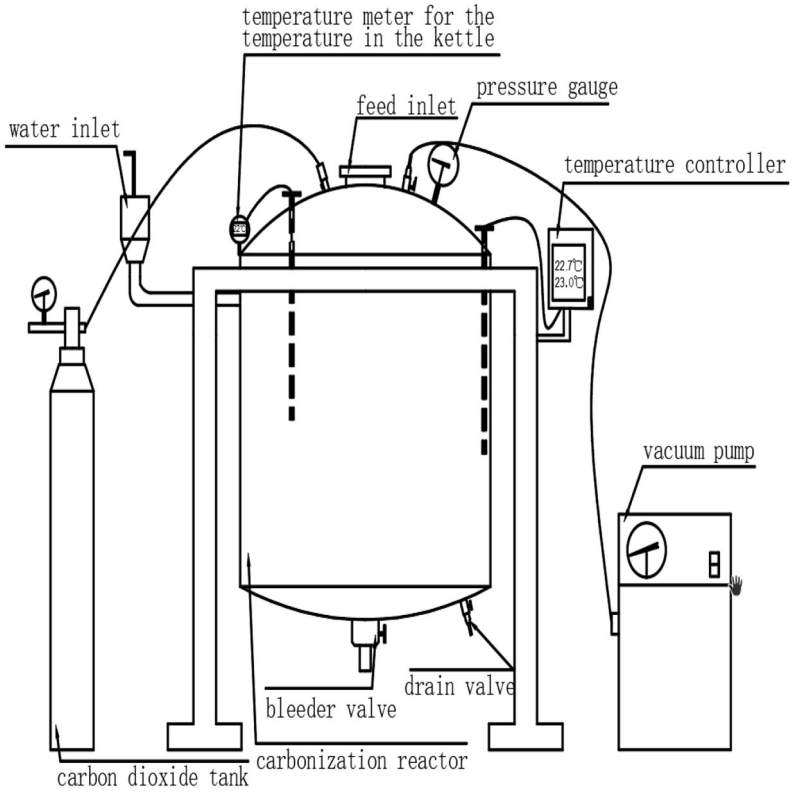
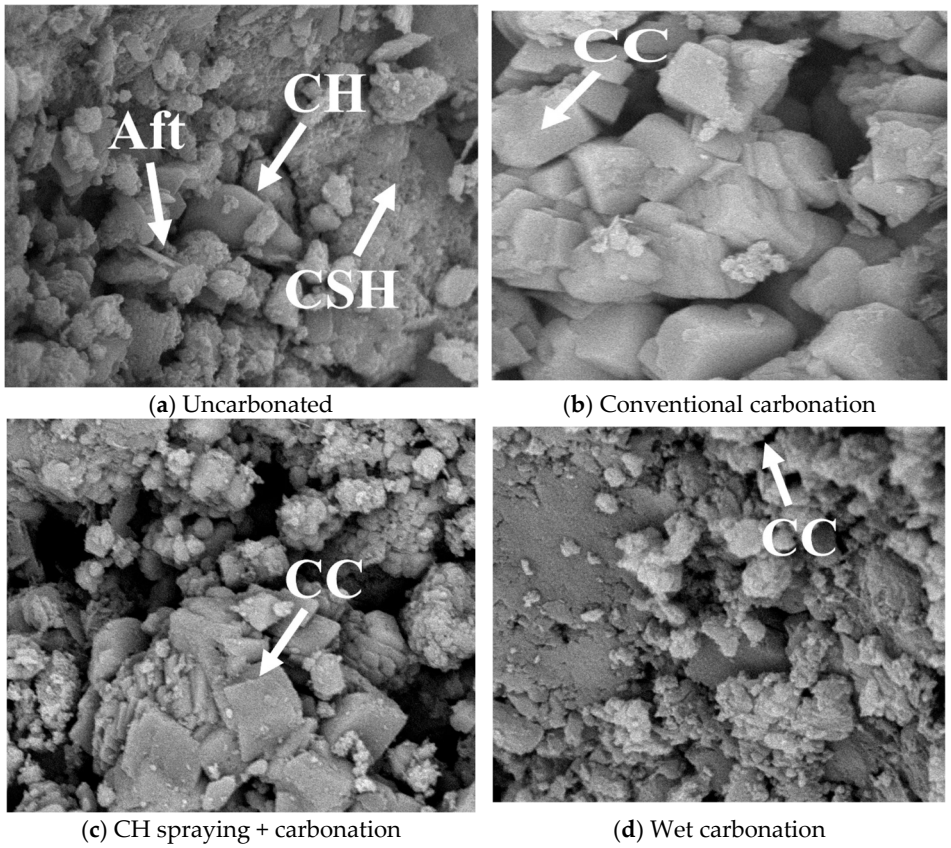


Figure 9. Schematic diagram of the carbonation test [107]. Reproduced from ref. [107]; licensed under CC BY 4.0.

Figure 10 presents SEM images of RFA, clearly illustrating the influence of different carbonation methods on its microstructural morphology [108]. Carbonation treatment reduces the aggregate's water absorption and interfacial pore space, thins the water film on the aggregate surface, and promotes the formation of pore-filling products, thereby significantly densifying the ITZ and reducing interfacial gaps. Moreover, pretreatment-assisted carbonation further increases the degree of carbonation and the filling effect, leading to a denser and narrower ITZ, ultimately improving the performance of recycled aggregate concrete and suppressing crack propagation under loading.



(**a**) Uncarbonated (**b**) Conventional carbonation

(**c**) CH spraying + carbonation (**d**) Wet carbonation

Figure 10. SEM images of FRCA before and after carbonation [108]. Adapted from ref. [108], cropped for clarity, content unchanged; licensed under CC BY 4.0.

After carbonation, a low Ca/Si ratio C–S–H gel and a $CaCO_3$-rich protective layer are formed, which reduce chloride ion permeability and enhance the durability of recycled aggregate concrete (RAC) [106]. At the same time, carbonation curing enables CO_2 sequestration, making it an efficient and environmentally friendly technique [106,109]. The carbonation processes and the effects of the treatment sequence are presented in Figure 11 [110].

4.3.2. Factors Influencing Carbonation Curing

Numerous studies have investigated the various factors affecting aggregate behavior during carbonation curing. It has been observed that low-strength parent concrete exhibits a higher degree of carbonation than high-strength parent concrete, and the resulting RAC shows greater improvement in compressive strength. This finding indicates that carbonation curing is particularly effective in enhancing the performance of low-quality RCA [106,111]. Moreover, low-strength parent concrete generally possesses higher permeability, which facilitates CO_2 diffusion and promotes more efficient carbonation curing [23]. Furthermore, when the water-to-binder ratio of the parent concrete is higher, the micro-

hardness of the old ITZ and old mortar increases more significantly, and the degree of carbonation becomes higher [112]. In addition, RCA that has been stored for a longer period typically undergoes partial natural carbonation in air. Consequently, its subsequent carbonation degree is lower than that of freshly prepared RCA. Xuan et al. summarized additional factors influencing carbonation, including particle size, moisture content, curing duration, and initial water absorption [113,114]. Zhan et al. reported that smaller RCA particles, due to their larger specific surface area, exhibit a higher degree of carbonation [114]. Excessive moisture content hinders CO_2 diffusion, whereas insufficient moisture limits the availability of the reaction medium [106]. The carbonation reaction rate is rapid during the first two hours of curing, then gradually slows and stabilizes after approximately 24 h [114]. Furthermore, because greater porosity facilitates CO_2 penetration, RCA with higher water absorption tends to carbonate more readily.

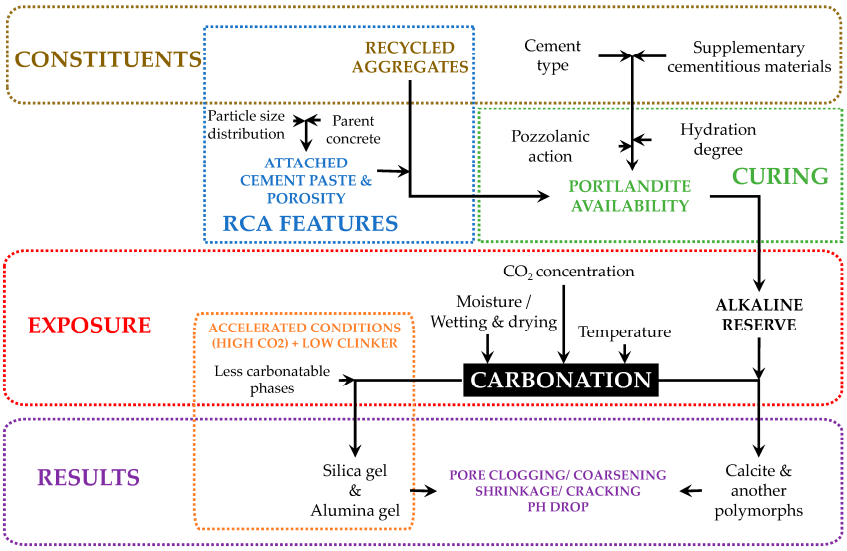


Figure 11. Process sequence of carbonation and its effects [110]. Reproduced from ref. [110], licensed under CC BY 4.0.

Other carbonation curing parameters, such as CO_2 concentration, CO_2 pressure, and relative humidity (RH), also significantly influence the carbonation degree of RCA. For instance, when treating RFA, the carbonation depth first increases and then decreases with rising CO_2 concentration. The optimum carbonation level occurs at approximately 70% CO_2, whereas, at 100% CO_2, surface densification impedes gas diffusion and thus reduces the overall carbonation extent [106]. Excessively high carbonation pressure can suppress the carbonation process and, under high-pressure conditions, may even induce microcracking risks [115]. Therefore, the applied CO_2 pressure should be maintained within an appropriate range [113,114]. Likewise, within a relative humidity (RH) range of 50%–80%, higher humidity levels hinder CO_2 diffusion, leading to a slight reduction in carbonation degree and strength. Hence, controlling humidity within an optimal range during carbonation curing is essential [113].

Zhan et al. investigated the effect of temperature on the carbonation of RAC containing RA, and found that, when the carbonation temperature increased from 20 °C to 80 °C, the compressive strength exhibited little variation [116]. This may be because higher temperature accelerates the dissolution of Ca^{2+} from silicate phases, thereby promoting carbonation. However, elevated temperature simultaneously reduces CO_2 solubility, raises pH, slows calcium dissolution, and intensifies moisture evaporation, which are factors that collectively inhibit the carbonation reaction. The positive and negative effects of temperature elevation on the carbonation reaction counteract each other, resulting in an

overall negligible influence [116,117]. Therefore, in practical applications, CO_2 curing can be effectively conducted at ambient temperature, eliminating the need for strict temperature control and reducing energy consumption.

4.3.3. Effects of Carbonation Curing on RA and RAC

The influence of different carbonation conditions on RA and RAC performance and the search for optimal curing parameters have been widely studied. For instance, Wu et al. systematically investigated various carbonation parameters, including pressure (0.5, 1, 2, and 4 bar), initial moisture content (1.00%, 1.81%, and 3.00%), and treatment duration (1, 3, and 12 h) [105]. Their results indicated that, while the highest performance was not achieved at 4 bar pressure, 1.81% moisture content, and 3 h of carbonation, this condition represented the optimal balance between performance, process stability, and practicality. Luo et al. performed carbonation treatment of recycled concrete aggregates (RCAs) in a high-pressure chamber with CO_2 concentrations $\geq$ 99.9%, at a pressure of 0.4 MPa for durations of 6, 12, 24, 48, and 72 h [104]. They identified 24 h as the optimal carbonation treatment time for improving the aggregate properties. Similarly, Li et al. used an accelerated carbonation setup to treat RCA for 7 days, under 100% CO_2 concentration and 1 bar pressure, further supporting the effectiveness of extended carbonation periods for enhancing RCA properties [106]. Zhang et al. explored carbonation treatment of recycled gravel and crushed stone under controlled conditions, using 20 °C temperature, 60% relative humidity, and 20% CO_2 concentration, showing significant improvements in aggregate properties under these conditions [103]. Zhan et al. performed carbonation in a sealed chamber where CO_2 was injected at a pressure of 10 kPa after applying a vacuum [114]. They evaluated the effect of different source concrete strengths (C30, C45, C60, and C80) on carbonation performance, suggesting that higher-strength parent concretes may yield different carbonation effects. Xuan et al. treated two types of RCA—new RCA (NRCA) and old RCA (ORCA)—under different CO_2 pressures (0.1 bar and 5.0 bar), finding that the treatment was most effective at 5.0 bar pressure [113]. Li et al. conducted carbonation curing of RCA at 20% CO_2 concentration, 70% relative humidity, and 20 °C for 0, 7, 14, and 28 days, with the results indicating that 28-day treatment led to the most significant improvement in aggregate properties [118].

The optimal parameters vary across studies, but extended carbonation periods, higher CO_2 concentrations, and specific pressure conditions generally lead to better enhancements in RA properties, highlighting the importance of carefully selecting curing conditions for maximizing performance.

Table 5 summarizes the effects of different carbonation treatments on RA performance. As shown in Table 5, the influence of carbonation on aggregate properties is not governed by any single factor but rather by the synergistic interaction of multiple parameters, such as temperature, initial moisture content, pressure, and carbonation duration. For example, variations in aggregate type or treatment conditions can lead to different optimal carbonation pressures and durations, emphasizing the need for parameter-specific optimization in practice. In addition, Zhan et al. observed that larger aggregates exhibited greater improvement than smaller ones [114], whereas Li et al. and Xuan et al. reported that smaller aggregates showed more pronounced enhancement [106,113]. Zhang et al. found that recycled crushed stone benefited more from carbonation than recycled gravel [103]. Both Zhan et al. and Xuan et al. also demonstrated that aggregates derived from lower-strength parent concrete experienced greater performance improvement than those from higher-strength sources [113,114].

Table 5. Effect of different carbonization treatments on aggregate properties [103–106,113,118,119].

Authors	Aggregate Type	Untreated RA			Optimal Treatment Condition	Carbonizing		
		Apparent Density/ (kg/m^3)	Water Absorption of Aggregate/%	Crush Value/%		Apparent Density/ (kg/m^3)	Water Absorption of Aggregate/%	Crush Value/%
Wu et al. [105]	RCA	2620	4.34	9.27	30 °C, 1. 81% moisture content, 1 bar pressure, 3 h carbonization.	2645	3.36	7.30
Luo et al. [104]	RCA (5–20 mm)	2633	3.25	13.42	CO_2 concentration ≥ 99.9%, pressure 0.4 MPa, 24 h	2647	2.37	12.78
Li et al. [106]	RCA (5–10 mm)	2611	6.22	—	CO_2 concentration 100%, pressure 1 bar, 7 d.	2621	5.31	—
	RCA (10–20 mm)	2583	6.19	27.8		2604	4.81	21.9
Zhang et al. [103]	RCA (gravel)	2530	8.06	18.6	20 °C, humidity 60%, CO_2 concentration 20%, atmospheric pressure	2650	5.78	16.9
	RCA (crushed stone)	2490	8.70	17.1		2630	6.73	15.8
Zhan et al. [119]	RCA30	2602	6.58	—	23 °C, CO_2 pressure 10 kPa, low humidity	2619	5.25	—
	RCA45	2591	5.42	—		2606	4.71	—
	RCA60	2662	4.97	—		2670	4.61	—
	RCA80	2670	4.62	—		2661	4.41	—
Xuan et al. [113]	NRCA (5–10 mm)	2624	7.2	—	CO_2 concentration 100%, 5.0 bar pressure, 24 h.	2663	6.0	—
	NRCA (10–20 mm)	2605	6.1	27.8		2609	5. 0	20.6
	ORCA (5–10 mm)	2557	6.4	—		2585	5.8	—
	ORCA (10–20 mm)	2561	5.5	26.6		2571	5.2	24.5
Li et al. [118]	RCA (10–20 mm)	2593	6.65	—	20 °C, CO_2 20%, humidity 70%, 28 d.	2617	4.29	—
	RCA (20–30 mm)	2586	6.68	—		2613	4.31	—
	RCA (30–40 mm)	2583	6.69	—		2611	4.35	—

Figure 12 summarizes the effects of different carbonation treatments of RA on the 28-day compressive strength of RAC. From Figure 12, the 28-day compressive strength increases in RAC under different carbonation treatments are 21.76%, 15.79%, 12.47%, 17.74%, 9.89%, 5.93%, and 23.38%, respectively. Carbonation curing is more effective in enhancing the 28-day compressive strength of low-strength RAC, as weaker matrices allow deeper CO_2 penetration and more complete reactions. In addition, RAC prepared with carbonated recycled gravel generally exhibits higher 28-day compressive strength than that made with carbonated recycled crushed stone, likely because gravel possesses a more intact particle shape and a lower proportion of elongated or flaky particles, which improves packing density and interfacial bonding. Among the various carbonation conditions applied to aggregates, the optimal parameters for enhancing the 28-day compressive strength of RAC are a temperature of 20 °C, 20% CO_2 concentration, 70% relative humidity, and a 28-day carbonation duration.

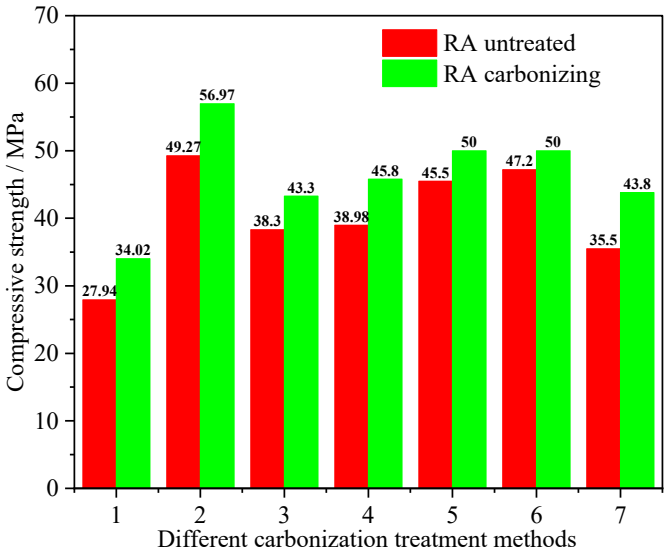


Figure 12. Influence of different carbonation treatments of RA on the 28-day compressive strength of RAC [103,106,119]. (Different carbonization treatment methods for coordinates 1–7: 1—RCA carbonated at 30 °C, 1.81% moisture content, 1 bar pressure for 3 h, with RAC of strength grade C25 [105], 2—RCA carbonated at 30 °C, 1.81% moisture content, 1 bar pressure for 3 h, with RAC of strength grade C40 [105], 3—RCA carbonated under 100% CO_2, 1 bar pressure for 7 days [104], 4—RCA carbonated under 100% CO_2, 1 bar pressure for 7 days [106], 5—recycled gravel carbonated at 20 °C, 60% RH, 20% CO_2, under ambient pressure [103], 6—recycled crushed stone carbonated at 20 °C, 60% RH, 20% CO_2, under ambient pressure [103], 7—RCA carbonated at 20 °C, 70% RH, and 20% CO_2 for 28 days [119]).

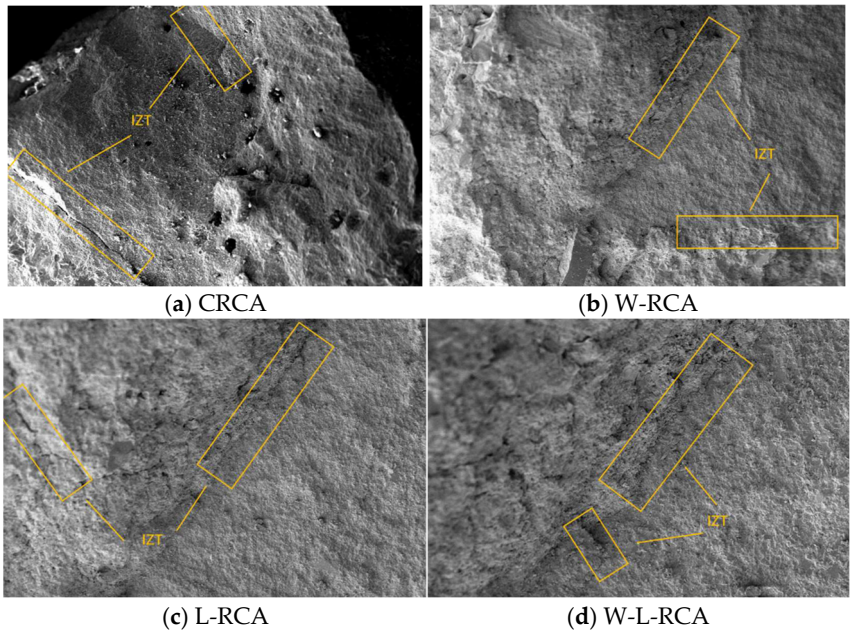
Figure 13 presents SEM images of the interfacial transition zone (ITZ) for recycled aggregate mortar with different treatment routes, including direct carbonation (CRCA), recycled coarse aggregate carbonized after ultrasonic cavitation pretreatment (W-RCA), recycled coarse aggregate carbonized after $Ca(OH)_2$ pre-soaking pretreatment (L-RCA) and recycled coarse aggregate carbonized after combined ultrasonic cavitation and $Ca(OH)_2$ pre-soaking pretreatment (W-L-RCA) [120]. It can be observed that, from Figure 13, carbonation treatment reduces the aggregate's water absorption and interfacial pore space, thins the water film on the aggregate surface, and promotes the formation of filling products, thereby significantly densifying the ITZ and reducing interfacial gaps. Moreover, pretreatment-assisted carbonation further enhances the degree of carbonation and the filling effect, resulting in a denser and narrower ITZ, ultimately improving the performance of recycled aggregate concrete and restraining crack propagation under loading.

To further improve carbonation treatment, pre-soaking RA in limewater prior to carbonation can enhance the degree of carbonation and thereby increase the compressive strength of RA [106]. The reason is that the additional $Ca(OH)_2$ introduced by the limewater provides more calcium sources within the old mortar, enabling the formation of extra $CaCO_3$ during carbonation. These products fill more pores and microcracks, resulting in a denser microstructure [23,121].

4.4. Summary

Acid treatment, polymer modification, and carbonation curing enhance recycled aggregate (RA) via distinct mechanisms, and their applicability depends on performance targets and practical constraints. Acid treatment removes adhered mortar and dissolves weak hydration products, reducing water absorption and improving particle quality, but overly aggressive conditions may etch the original aggregate and require chemical handling and wastewater neutralization. Polymer modification forms a coating and/or fills accessible

pores to improve moisture resistance and the interfacial transition zone (ITZ), yet its performance is sensitive to polymer type and dosage and may be limited by cost and long-term durability. Carbonation curing forms carbonate products that densify pores and stabilize attached mortar, offering a sustainability-oriented route (with potential CO_2 uptake), but it requires controlled CO_2 concentration.



(**a**) CRCA (**b**) W-RCA

(**c**) L-RCA (**d**) W-L-RCA

Figure 13. ITZ micro-morphology of recycled aggregates under different carbonation treatment pathways [120]. Adapted from ref. [120] cropped for clarity (content unchanged); licensed under CC BY 4.0.

From an engineering perspective, acid treatment is preferred for rapid mortar removal when effluent management is feasible; polymer modification is preferred when surface sealing and interfacial improvement are prioritized and cost is acceptable; and carbonation curing is preferred when attached mortar densification and sustainability are emphasized under controlled curing. In terms of compatibility, carbonation is better positioned as a pre-treatment because it relies on CO_2 ingress, whereas polymer sealing may hinder subsequent carbonation; conversely, carbonation followed by polymer coating can be synergistic when both densification and long-term moisture resistance are required.

5. Biological Strengthening

Biological strengthening generally refers to the microbially induced calcium carbonate precipitation (MICP) method. Its core mechanism relies on the metabolic activity of specific microorganisms to drive chemical reactions that generate mineral precipitates (such as $CaCO_3$), which are then deposited on the surface or within the pores of the target material [122].

5.1. Biological Deposition

5.1.1. Overview

The application of biological deposition technology was first demonstrated by Gollapudi et al., who used bacterial mineralization to control leakage in construction materials, thereby validating the feasibility of this technique [123]. Today, this approach is widely applied in self-healing concrete, where bacterial self-repair mechanisms enable the autonomous sealing of cracks and enhance the sustainability and durability of concrete [124,125]. In addition, several researchers have explored recycled aggregate (RA)

pretreatment using microbial deposition to improve aggregate quality, or have incorporated bacteria directly during the mixing process to enhance the performance of recycled aggregate concrete (RAC), leveraging biologically induced $CaCO_3$ precipitation to refine the microstructure and strengthen the interfacial transition zone (ITZ).

Microorganisms used in the biological deposition method are generally classified into two types based on their metabolic pathways: autotrophic and heterotrophic [124]. The autotrophic type induces $CaCO_3$ precipitation through CO_2 fixation, a process that avoids ammonia emissions and is particularly effective for fine aggregates (maximum particle size of about 5 mm) [126]. The heterotrophic type, on the other hand, induces carbonate precipitation via microbial urea decomposition, where urease-producing bacteria hydrolyze urea to generate carbonate ions, leading to $CaCO_3$ formation [127]. The ureolytic bacteria commonly used for biological deposition predominantly belong to the *Bacillus* genus, including *Bacillus subtilis* [128], *Sporosarcina pasteurii* [129], and *Bacillus sphaericus* [130]. Among these, *Sporosarcina pasteurii* is the most widely applied because it produces higher levels of urease, remains highly active under extreme environmental conditions [131], and is non-pathogenic [132], making it particularly suitable for engineering applications.

The mechanism of ureolytic bacteria involves the microbial production of urease, which catalyzes the hydrolysis of urea into carbonate and ammonia. This reaction elevates both the carbonate concentration and pH of the surrounding environment. Subsequently, carbonate and ammonia undergo further hydrolysis to produce ammonium ions (NH_4^+) and carbonate ions (CO_3^{2-}) [124]. The bacteria then attract calcium ions (Ca^{2+}) to their negatively charged cell surfaces, facilitating the combination of CO_3^{2-} and Ca^{2+} to form calcium carbonate ($CaCO_3$) crystals [122]. The precipitated $CaCO_3$ deposits on the surface of the RA, filling pores and microcracks and thus improving aggregate performance. The detailed reaction process is shown in Equations (11)–(17) [124,125,127,131]. The general procedure for bio-deposition on RA is shown in Figure 14 [133].

$$CO(NH_2)_2 + H_2O \rightarrow NH_2COOH + NH_3 \quad (11)$$

$$NH_2COOH + H_2O \rightarrow NH_3 + H_2CO_3 \quad (12)$$

$$H_2CO_3 \leftrightarrow HCO_3^- + H^+ \quad (13)$$

$$2NH_4 + 2H_2O \leftrightarrow 2NH_4^+ + 2OH^- \quad (14)$$

$$HCO_3^- + H^+ + 2NH_4^+ + 2OH^- \leftrightarrow CO_3^{2-} + 2NH_4^+ + 2H_2O \quad (15)$$

$$Ca^{2+} + Cell \rightarrow Cell{-}Ca^{2+} \quad (16)$$

$$Cell{-}Ca^{2+} + CO_3^{2-} \rightarrow Cell{-}CaCO_3 \downarrow \quad (17)$$

In fact, because bacteria are relatively large and only a limited number of pores in cement-based materials can accommodate them, MICP is generally regarded as a surface treatment technique [122,134]. Studies have shown that the $CaCO_3$ formed through microbial deposition bonds strongly with both the old mortar on the aggregate and the new cement matrix, resulting in RAC made from bio-deposited RCA exhibiting higher compressive strength than conventional NAC [135]. In addition, studies have indicated that drying treatment can damage bacteria adhered to the aggregate surface, thereby reducing the biomineralization efficiency and leading to a decrease in the strength of the resulting concrete compared with specimens subjected to standard microbial treatment [136].

Figure 15 presents SEM images comparing the surface morphology of RA before and after microbial treatment [137]. As shown in Figure 15, compared with untreated RA, MICP treatment forms a relatively uniform layer of calcium carbonate crystals (1–10 μm) on the RA surface; pores of approximately 0.5 μm on the spherical crystals may reflect bacterial

imprints formed during the mineralization process. These findings indicate that the bacteria not only drive calcite precipitation via enzymatic activity but also act as nucleation sites, generating a protective crystalline layer that effectively fills or covers pores and microcracks on RA.

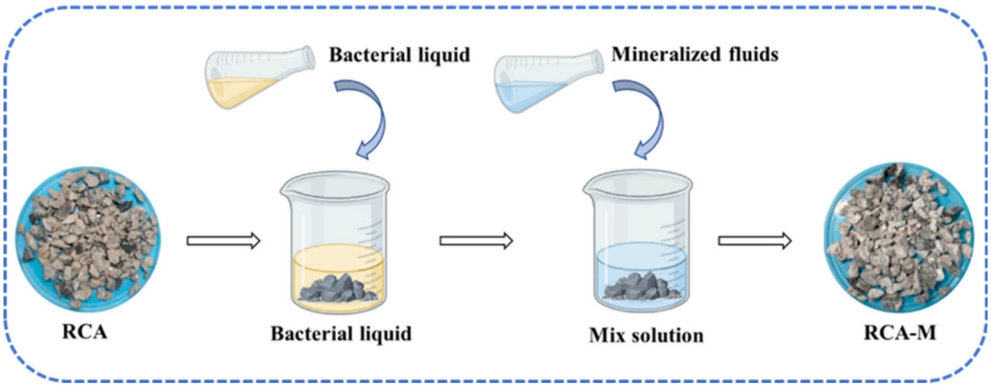
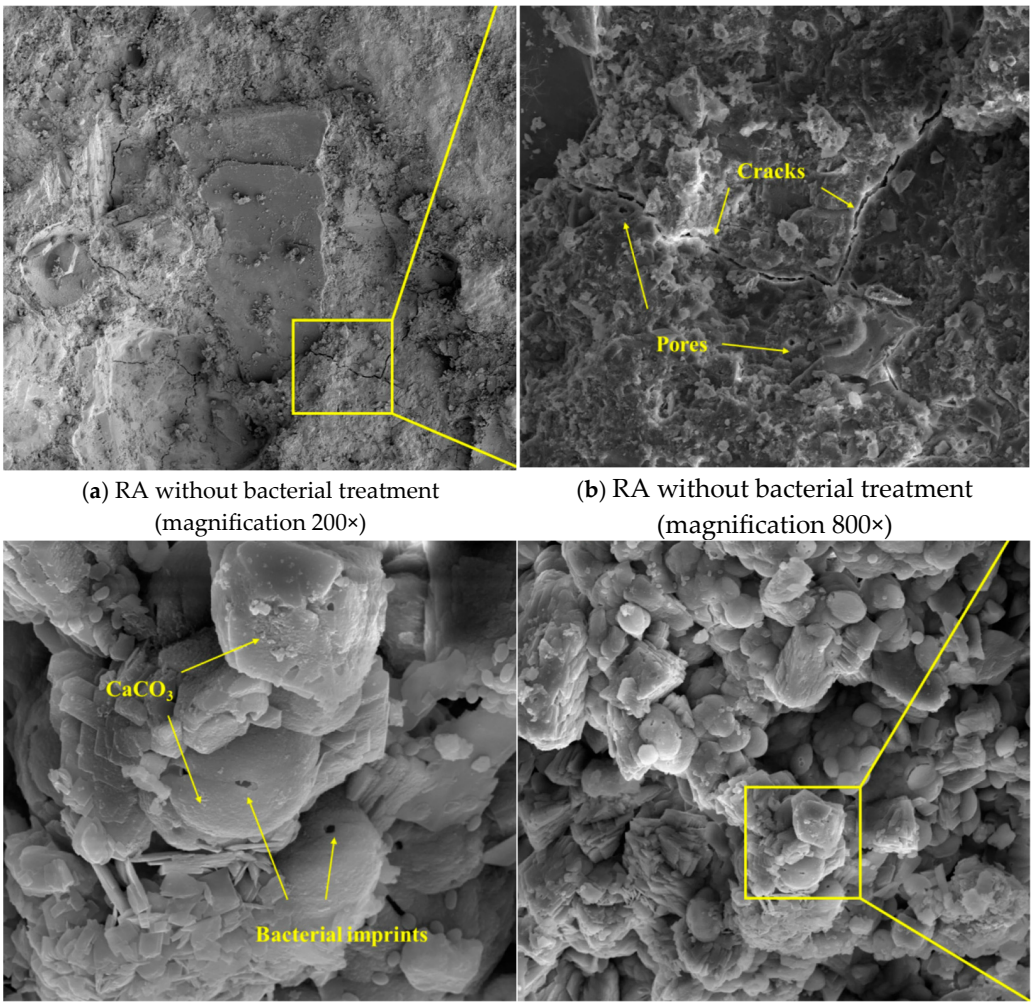


Figure 14. Schematic diagram of the bio-deposition procedure [133]. Reproduced from ref. [133]; licensed under CC BY 4.0.



(**a**) RA without bacterial treatment (magnification 200×)

(**b**) RA without bacterial treatment (magnification 800×)

(**c**) RA with bacterial treatment (magnification 3000×)

(**d**) RA with bacterial treatment (magnification 10,000×)

Figure 15. SEM comparison of RA surfaces before and after bacterial treatment [137]. Adapted from ref. [137]; cropped for clarity (content unchanged); licensed under CC BY 4.0.

In addition, Wu et al. compared the ITZ characteristics of untreated RA with those subjected to immersion and spraying treatments [27]. The results clearly showed that the ITZ cracks in both treated groups were much narrower than those in the untreated aggregates, confirming that bio-deposition positively enhances the microstructural integrity of the interfacial transition zone and improves the bonding quality at the aggregate–paste interface.

5.1.2. Enhancement of RA, RAC, and RAM Performance by Biological Deposition

The key factors influencing the efficiency of biological deposition include pH value, temperature, bacterial concentration, and calcium ion concentration. According to Wong et al., who investigated ureolytic *Bacillus* species in cement-based materials during microbially induced calcite precipitation (MICP), the bacterial concentration is the most critical factor affecting both the urea hydrolysis rate and the amount of $CaCO_3$ precipitated [134]. The optimal temperature range for microbial-induced calcite precipitation is 20–37 °C, while temperatures below this range significantly reduce the reaction rate. An elevated pH (around 9) promotes bacterial activity and enhances $CaCO_3$ precipitation efficiency. The type of calcium source, such as calcium chloride or calcium acetate, also influences both the precipitation efficiency and the resulting material properties. Additionally, the water-to-cement ratio (W/C) plays an important role: For mortars with higher W/C ratios, biological deposition tends to be more effective, leading to greater strength improvements in the resulting RAC [126]. In addition, Qiu et al. incorporated *Sporosarcina pasteurii* directly into RAC and demonstrated that optimizing the culture conditions, which include pH, temperature, bacterial concentration, and calcium ion concentration, can significantly enhance the efficiency of $CaCO_3$ deposition [138]. Their study found that, under the conditions of pH = 9.5, temperature = 35 °C, high bacterial concentration (108 cells/mL), and $CaCl_2$ concentration = 16.8 g/L, the carbonate precipitation efficiency reached its optimum, effectively increasing the carbonate content of the RCA, reducing their water absorption, and improving the overall quality of the resulting RAC.

In studies on MICP pretreatment of RA and its impact on RAC performance, Gong et al. utilized a spectrophotometer to determine bacterial concentrations of *Sporosarcina pasteurii* with OD_{600} values of 0.8, 1.0, and 1.2 [52]. They applied these bacterial solutions to a mixed recycled aggregate (RMA) composed of recycled concrete aggregate and recycled brick aggregate, conducting curing treatments for 1, 2, 3, 5, and 7 days under various conditions. The results revealed that the optimal treatment parameters were a bacterial concentration of OD_{600} = 1.2 and a curing duration of 5 days. Wu et al. employed *Bacillus pseudofirmus* with a bacterial concentration of approximately 1.9 × 108 cells/mL to treat RA of varying particle sizes under ambient temperature conditions for 20 days, and subsequently evaluated the improvement in the performance of recycled aggregate mortar (RAM) [126]. Wang et al. employed an alkali-resistant strain of *Bacillus sphaericus* to improve both RCA and RMAs, which comprise crushed concrete, masonry materials, glass, and wood, using three different treatment methods: spraying, single immersion, and double immersion [135]. Feng et al. utilized *Sporosarcina pasteurii* and obtained a high bacterial concentration through centrifugation [136]. The RFA were treated under optimized precipitation conditions (pH = 9.5, bacterial concentration = 108 cells/mL, calcium concentration = 0.55 mol/L, and temperature = 30 °C) for durations of 3, 7, 10, and 14 days. Wu et al. used Bacillus strains to compare the effectiveness of immersion and spraying methods in treating RFA [27]. The results showed that the immersion method produced more uniform and continuous $CaCO_3$ deposition on the aggregate surface, leading to better improvement in aggregate quality and mechanical performance. To investigate the effects of different calcium sources, Zhan et al. further investigated the effects of different calcium sources, comparing calcium chloride ($CaCl_2$) and calcium nitrate ($Ca(NO_3)_2$) for their effectiveness in enhancing RFA

performance when treated with *Sporosarcina pasteurii* [139]. Their results provided insights into the influence of calcium sources on the MICP process.

In addition, Sahoo et al. introduced *Bacillus subtilis* directly into freshly mixed RAC at four different cell concentrations (10^1, 10^3, 10^6, and 10^7 cells/mL) to investigate the effect on the mechanical properties of the concrete [128]. The results showed that, when the bacterial concentration was 10^6 cells/mL, the compressive strength of RAC exhibited the most significant improvement, indicating that an optimal bacterial concentration exists beyond which further increases do not enhance, and may even hinder, the mechanical performance due to bacterial clustering or uneven $CaCO_3$ precipitation.

These studies collectively highlight that MICP pretreatment using various bacterial strains, concentrations, and curing conditions can significantly improve the properties of recycled aggregates and RAC. However, the effectiveness of the treatment is influenced by factors such as bacterial concentration, curing time, treatment method, and the type of calcium source used, emphasizing the need to optimize these parameters for maximum improvement in RAC performance.

Table 6 summarizes the modification effects of different bacterial treatments on RA after pretreatment. As shown in Table 6, studies indicate that smaller aggregate particle sizes exhibit more pronounced performance improvement following microbial treatment, due to the larger specific surface area available for bacterial adhesion and $CaCO_3$ precipitation. Moreover, the spraying method generally demonstrates better enhancement efficiency than the immersion method, as it ensures more uniform bacterial distribution and improved surface mineralization without excessive pore saturation or bacterial loss. In addition, although extending the pretreatment duration generally has a positive effect on improving aggregate properties, the marginal benefits gradually diminish over time. Compared with the immersion method, the spraying technique yields more pronounced results as it likely provides sufficient oxygen, thereby promoting greater $CaCO_3$ deposition and leading to more significant enhancement in RFA performance. Furthermore, when comparing calcium sources, $CaCl_2$ has been shown to produce more substantial improvements in the physical and mechanical properties of RFA than $Ca(NO_3)_2$, owing to its higher ionic availability and faster precipitation kinetics.

Table 6. Modification effect of different bacteria on RA after pretreatment [27,52,126,135,136,139].

Name of Bacteria	Aggregate Type	Untreated RA			Pretreatment Conditions	Biological Treatment of RA		
		Apparent Density/ (kg/m^3)	Water Absorption of Aggregate/%	Crush Value/%		Apparent Density/ (kg/m^3)	Water Absorption of Aggregate/%	Crush Value/%
Bacillus pasteurii [52]	RMAs	2406	9.14	23.3	Optimal treatment condition	2501	7.44	18.1
Bacillus pseudofirmus [126]	RCA (20 mm)	2650	5.0	17.1	Optimal treatment condition	2677	4.5	14.5
	RCA (10 mm)	2630	5.8	—		2656	5.0	—
	RFA (5 mm)	2500	8.5	20.5		2625	6.5	18.0
Bacillus [27]	RFA	—	12.7	23.2	Soaking	—	9.8	21.4
					Spray coating	—	9.1	20.7
Bacillus sphaericus [135]	RCA	—	5	—	The optimum treatment conditions for secondary soaking (bacteria + deposition solution)	—	4.0	—
	RMAs	—	7.5	—		—	5.5	—

Table 6. *Cont.*

Name of Bacteria	Aggregate Type	Untreated RA			Pretreatment Conditions	Biological Treatment of RA		
		Apparent Density/ (kg/m^3)	Water Absorption of Aggregate/%	Crush Value/%		Apparent Density/ (kg/m^3)	Water Absorption of Aggregate/%	Crush Value/%
Sporosarcina pasteurii [136]	RFA	—	24.5	—	Optimal treatment condition, 3 d	—	19.1	—
					Optimal treatment condition, 7 d	—	17.8	—
					Optimal treatment condition, 10 d	—	17.5	—
					Optimal treatment condition, 14 d	—	16.8	—
Sporosarcina pasteurii [139]	RFA	—	4.35	18	Calcium source: $CaCl_2$	—	2.62	12
					Calcium source: $Ca(NO_3)_2$	—	3.10	13

Figure 16 summarizes the improvement in the 28-day compressive strength of RAC and RAM after biological deposition treatment. From Figure 16, the improvements in 28-day compressive strength for RAC and RAM after biological deposition are 19.3%, 36.5%, 20.9%, 40.7%, 15.9%, 14.4%, 29.0%, and 22.6%, respectively. After bacterial treatment, the RAM with W/C = 0.5 exhibited higher strength than that with W/C = 0.35, likely due to improved microbial activity and more favorable conditions for $CaCO_3$ precipitation at higher water content. Additionally, RAC prepared from strengthened RMAs showed a greater improvement in strength than that from RCA alone, demonstrating the efficiency of biological reinforcement in heterogeneous RA. Furthermore, when $CaCl_2$ was used as the calcium source, the enhancement in recycled mortar performance was more significant than with $Ca(NO_3)_2$, owing to the ability of $CaCl_2$ to induce more abundant and denser $CaCO_3$ precipitation, which strengthens the microstructure and interfacial bonding.

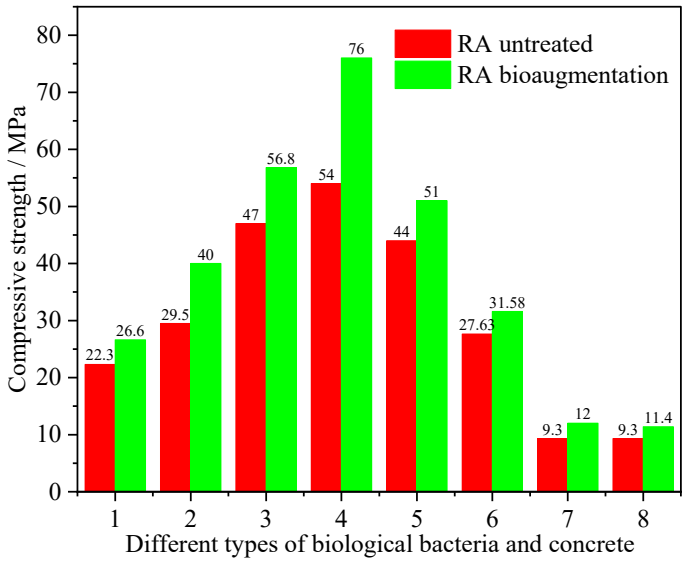


Figure 16. Improvement in the 28-day compressive strength of RAC and RAM under different biological strengthening treatments [52,126,135,136,139]. (Different types of biological bacteria and concrete for coordinates 1–8: 1—*Sporosarcina pasteurii*-treated aggregates used to produce RAC [52], 2—*Bacillus pseudofirmus*-treated aggregates used to produce RAM (W/C = 0.5) [126], 3—*Bacillus pseudofirmus*-treated aggregates used to produce RAM (W/C = 0.35) [126], 4—*Sporosarcina pasteurii*-treated aggregates used to produce RAC [135], 5—*Sporosarcina pasteurii*-treated RMAs used to produce RAC [135], 6—*Sporosarcina pasteurii*-treated aggregates used to produce RAM [136], 7—*Sporosarcina*

pasteurii with $CaCl_2$ as the calcium source used to produce RAM [136], 8—*Sporosarcina pasteurii* with $Ca(NO_3)_2$ as the calcium source used to produce RAM [139]).

The biological deposition technique holds great potential for future development. However, several challenges remain to be addressed, including high cost, long-term sustainability, and bacterial tolerance under harsh conditions. Future research should focus on: developing efficient and low-cost bacterial encapsulation materials, such as magnetic nanoparticles, to improve bacterial stability and reusability; utilizing industrial or agricultural waste as nutrient sources to reduce treatment costs and enhance environmental sustainability; and exploring multi-species microbial consortia to achieve synergistic mineralization and higher self-healing or strengthening efficiency in RA and concrete systems [125].

5.2. Summary

MICP can fill pores and microcracks in the AM and densify the surface layer, thereby reducing water absorption. Compared with purely physical or chemical approaches, bio-deposition has attracted attention for its mild processing conditions and potential sustainability benefits; however, its effectiveness is strongly governed by biological activity and the reaction environment (e.g., microbial species, nutrient supply, calcium source, pH, temperature, and treatment duration), and practical limitations may arise in terms of processing time, reproducibility, and scale-up. Therefore, bio-deposition is particularly promising for applications where durability-oriented surface densification is desired and longer treatment times are acceptable, while further efforts are still needed to standardize protocols and improve engineering feasibility.

6. Discussion

To determine which treatment approach is the most effective and practically implementable, it is insufficient to consider only the extent to which each method improves the performance of recycled aggregate (RA) and recycled aggregate concrete (RAC). A comprehensive assessment should also account for engineering feasibility and scalability, including the required equipment and infrastructure, energy demand, overall treatment cost, production cycle and throughput, process complexity and controllability, and the recovery yield of RA.

6.1. Comparative Effectiveness of Different Strengthening Techniques

To compare the effectiveness of strengthening strategies for RCA, RFA, and RMAs, Table 7 summarizes the performance gains achieved by the six techniques reviewed in this study.

Table 7. Comparison of performance improvements of RA achieved by different strengthening treatments [27,52–54,58,68,72,73,75,79,80,84,88,100,101,103–106,113,118,119,126,135,136,139]. (↑: Increase, ↓: Decrease).

Strengthening Techniques	Aggregate Type	Apparent Density		Water Absorption of Aggregate		Crush Value	
		Range	Average	Range	Average	Range	Average
Mechanical strengthening [52–54,58]	RCA	↑ 14.08%~37.22%	↑ 14.82%	↓ 17.21%~90.61%	↓ 45.63%	—	—
	RFA	—	—	—	—	—	—
	RMAs	—	↑ 3.24%	—	↓ 17.25%	—	↓ 22.82%
Microwave heating [72,73,75]	RCA	↑ 1.97%~9.21%	↑ 4.84%	↓ 28.36%~77.22%	↓ 40.68%	↓ 27.66%~82.43%	↓ 49.58%
	RFA	—	—	—	—	—	—
	RMAs	—	—	—	—	—	—

Table 7. *Cont.*

Strengthening Techniques	Aggregate Type	Apparent Density		Water Absorption of Aggregate		Crush Value	
		Range	Average	Range	Average	Range	Average
Acid solution [58,68,79,80,84]	RCA	↑ −0.43%~7.29%	↑ 2.18%	↓ −4.28%~48.08%	↓ 17.32%	↓ 0.99%~9.09%	↓ 5.61%
	RFA	—	↑ 3.52%	—	↓ 34.09%	—	—
	RMAs	—	—	—	—	—	—
Polymer treatment [88,100,101]	RCA	↑ 0.40%~2.02%	↑ 1.26%	↓ 6.35%~69.33%	↓ 49.27%	—	—
	RFA	—	—	—	—	—	—
	RMAs	—	—	—	—	—	—
Carbonation curing treatment [103–106,113,118,119]	RCA	↑ −0.34%~5.62%	↑ 1.20%	↓ 5.45%~35.49%	↓ 19.89%	↓ 4.77%~25.90%	↓ 13.97%
	RFA	—	—	—	—	—	—
	RMAs	—	—	—	—	—	—
Biological deposition [27,52,126,135,136,139]	RCA	—	↑ 1.00%	—	↓ 14.60%	—	↓ 15.20%
	RFA	—	—	↓ 22.04%~39.77%	↓ 28.00%	↓ 7.76%~33.33%	↓ 18.37%
	RMAs	—	↑ 3.95%	—	↓ 22.63%	—	↓ 22.32%

A subset of the entries in Table 7 could not be subjected to meaningful statistical summarization because the underlying sample size was too small, or because the available data points were sparse and originated from the same experimental program, which limits representativeness and increases the risk of study-specific bias. Moreover, the strengthening dataset compiled in this review is dominated by RCA, whereas comparable data for RFA and RMAs remain limited. This imbalance largely reflects the current mainstream research focus, which has predominantly prioritized RCA strengthening over RFA and RMAs.

As shown in Table 7, the above treatment methods can, overall, effectively improve the performance of RA. Taking RCA as an example, the data indicate that physical strengthening achieves a relatively better overall improvement; polymer treatment can significantly reduce RCA water absorption, but its improvement in apparent density is relatively limited; carbonation treatment and bio-deposition are generally comparable in terms of the overall magnitude of improvement. For RFA, only acid treatment and bio-deposition in this study provide data that can be used for comparison, and the bio-deposition-related data are relatively more abundant, which also reflects that this direction has attracted greater attention in RFA strengthening research; based on the available results, bio-deposition shows relatively stable and effective improvement for RFA. For RMAs, existing studies report that their performance can be improved, but, due to the large differences in the composition of mixed aggregates and inconsistent original sources, it is difficult to conduct a cross-study comparison, and thus to determine which method has a greater advantage.

The comparison of compressive strength enhancements in RAC and RAM after RA modification is shown in Figure 17. As can be seen from Figure 17, all modification approaches can effectively increase the compressive strength of both RAC and RAM. Notably, the compressive strength improvement of RAC associated with polymer treatment exhibits considerable dispersion. This may be related to an insufficient sample size and differences in data sources (e.g., inconsistent baseline strengths and test conditions); it may also indicate that the effectiveness of polymer modification on RCA is more sensitive to the coupling of multiple factors (such as polymer type and dosage, coating uniformity, curing regime, the original quality of RCA, and its moisture condition), leading to greater variability in outcomes and making the effect more difficult to control consistently than for other methods.

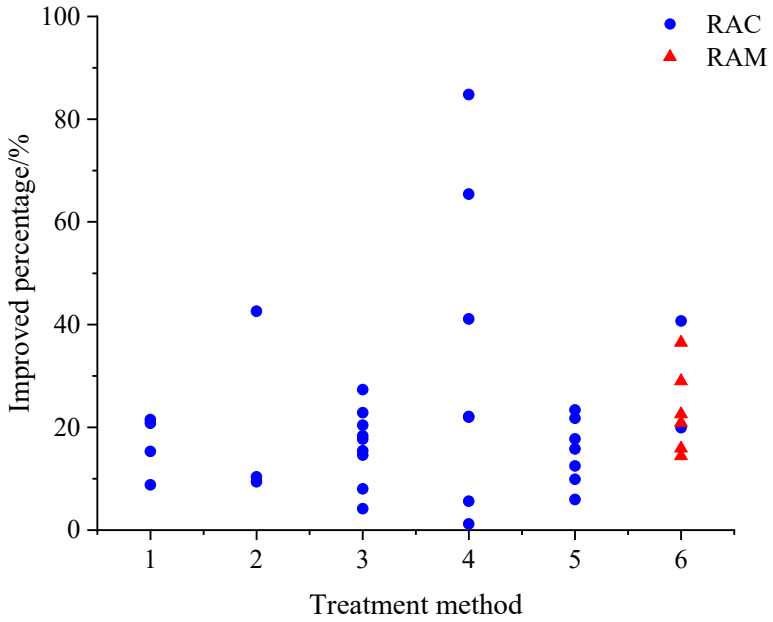


Figure 17. Compressive strength improvement of RAC and RAM under different modification methods [52,53,58,72,73,78,79,84,88,100,101,103–106,119,126,135,136,139]. (Different treatment methods for coordinates 1–8: 1—mechanical strengthening [52,53,58], 2—microwave heating [72,73], 3—acid treatment [58,78,79,84], 4—polymer treatment [88,100,101], 5—carbonation treatment [103–106,119], 6—bio-deposition [52,126,135,136,139]).

RAC is evaluated in this review primarily in terms of compressive strength, density, and water absorption, as these metrics are widely used and serve as key indicators of overall concrete performance. Compressive strength directly governs structural safety; density is closely associated with strength and durability; and water absorption influences durability, particularly with respect to freeze–thaw resistance and impermeability. Nevertheless, the available literature provides limited data on other performance-related properties, such as shrinkage, creep, chloride ion permeability, and freeze–thaw durability. Although these properties are equally important for practical applications, further research is needed due to experimental constraints and the current lack of sufficient datasets. Future studies should therefore place greater emphasis on these aspects—particularly under extreme environmental conditions—to generate more comprehensive experimental evidence in support of the reliable application of recycled aggregate concrete.

6.2. Advantages and Limitations of Different Treatment Methods

Mechanical strengthening can improve recycled aggregate quality and broaden its applicable range. Its main drawbacks are the relatively high energy demand and increased processing cost; moreover, excessive processing may undesirably alter particle shape/gradation and induce additional damage, and the improvement can be limited in some cases.

Microwave heating can improve aggregate quality and may offer energy advantages while reducing damage relative to conventional thermal treatments. However, the required equipment investment is relatively high; non-uniform treatment may occur during processing; the effectiveness can be constrained for large, thick, or highly irregular particles; and the method is not universally applicable to all aggregate types.

Acid treatment can improve aggregate quality and often reduces water absorption, which may translate into the enhanced performance of recycled concrete. Nevertheless, it may introduce durability concerns if chloride and sulfate ions are incorporated (e.g., increased risk of reinforcement corrosion and sulfate-related expansion), and it often

entails high reagent consumption and cost, along with corrosion hazards and stringent safety/handling requirements; improper treatment may also adversely affect aggregate integrity [80]. By comparison, acetic acid treatment is generally considered milder, cleaner, and potentially more cost-effective.

Polymer treatment can enhance the strength of recycled concrete and is often beneficial in reducing water absorption. Its limitations include higher material and processing costs, strong dependence of efficacy on polymer type and dosage (as well as treatment uniformity), potential impacts on fresh-state workability, and the need to address environmental considerations and end-of-life disposal.

Carbonation treatment can improve aggregate quality and the performance of recycled concrete, while offering potential CO_2 sequestration benefits. However, its effectiveness is highly sensitive to process conditions, requiring tight control and potentially additional equipment investment; improvements may be limited in depth; and, under certain conditions, carbonation may also be associated with shrinkage-related effects or increased brittleness.

Bio-deposition (MICP) has been reported to enhance both the strength and durability of recycled concrete and is generally regarded as a relatively mild and environmentally friendly approach. However, large-scale implementation remains challenging; the treatment effect can be highly scattered and difficult to control; the use of $CaCl_2$ as a calcium source may leave residual chloride and increase reinforcement corrosion risk; the cost of culture media and nutrients can be substantial [134]; and the attainable enhancement may be limited in some cases [127].

When selecting an appropriate treatment strategy for RAC, the decision should not be based solely on performance enhancement. A holistic evaluation is required, considering the effectiveness of RCA improvement alongside practical constraints such as treatment cost, energy demand, production cycle and throughput, process complexity and controllability, and aggregate recovery yield. Table 8 provides an integrated comparison of the representative methods and summarizes their overall practicality and recommended applicability.

Table 8. Integrated comparison of different treatment methods and their recommended applicability [45,72,77,80,87,88,126,129,140–151].

Treatment Method	Treatment Cost	Energy Consumption	Production Cycle	Environmental Burden	Industrial Feasibility	Recommendation
Mechanical strengthening [45,140,141]	High	Moderate	Short	Low	High	High
Microwave heating [72,142–144]	High	High	Moderate	Low	Moderate	Moderate
Acid solution [77,80]	Moderate	Low	Short	High	High	Low
Polymer treatment [87,88,145,146]	High	Low	Moderate	High	Moderate	Moderate
Carbonation curing treatment [140,145,147,148]	Low	Low	Moderate	Low	High	High
Biological deposition [126,129,149–151]	Moderate	Low	Long	Very low	Low	Low

From the perspective of practical deployment, carbonation treatment appears to be the most promising single strengthening route. Its key advantages include a comparatively stable treatment effect, good industrial scalability, and an attractive environmental profile due to its potential for CO_2 sequestration. Moreover, carbonation tends to deliver more comprehensive improvements across critical indicators and lends itself to standardized, streamlined process control. By contrast, microwave treatment is constrained by high equipment investment and challenges in achieving uniform heating; strong-acid treatments

(e.g., HCl or H_2SO_4) may introduce aggressive ions and thus raise durability concerns; polymer-based treatments face relatively high material and processing costs and potential environmental burdens associated with handling and disposal; and MICP, while often considered environmentally benign, still faces major bottlenecks in treatment time, cost, and consistency upon scale-up.

Looking ahead, MICP research should prioritize cost reduction, improved treatment repeatability, and shortened processing time. For acid treatment, efforts should focus on enhancing acid-use efficiency and developing recovery/recycling strategies to reduce waste-liquid handling costs. Polymer modification would benefit from exploring low-cost, biodegradable alternatives to mitigate both economic and end-of-life burdens. For microwave heating, improving heating uniformity and energy efficiency—potentially in combination with other techniques—will be critical for achieving reliable performance gains.

In engineering practice, a "mechanical strengthening + carbonation" route is frequently adopted. Mechanically strengthening the aggregate—through impurity removal and grading—can reduce feedstock variability and improve baseline aggregate quality, thereby providing a more consistent substrate for subsequent modification. Building on this, carbonation is more likely to yield a uniform and stable enhancement, leading to more reliable improvements in water absorption, compactness, interfacial quality, and durability. Importantly, both steps can be integrated into existing production lines and translated into standardized workflows, offering clear advantages in quality assurance, cost control, and large-scale implementation.

7. Conclusions and Outlook

7.1. Conclusions

This study systematically reviewed and compared various reinforcement methods for recycled aggregate (RA) such as physical, chemical, and biological strengthening techniques, analyzing their mechanisms, influencing factors, and effects on the mechanical performance of RAC. The main conclusions are as follows:

(1) Traditional mechanical strengthening methods developed abroad generally suffer from drawbacks such as bulky equipment, complex processes, high wear rates, and elevated production costs. In contrast, the improved particle-shaping method effectively mitigates several of these issues, leading to significant enhancement in aggregate quality. Furthermore, key parameters such as grinding duration, machine configuration, and rotation speed play a decisive role in determining the efficiency of mortar removal. When combined with heating treatment, the mechanical modification process yields superior improvements in both the properties of RA and the performance of the corresponding RAC.

(2) The microwave heating method requires relatively low energy consumption and shorter treatment duration, while significantly improving the properties of both RA and RAC. Key parameters influencing its effectiveness include microwave power, heating duration, number of microwave cycles, concrete mix proportion, and aggregate moisture content. Proper optimization of these factors ensures efficient removal of AM and enhancement of interfacial bonding, leading to improved mechanical strength of the resulting recycled concrete.

(3) Acid solution treatment can effectively remove the AM from the surface of RA. The type of acid, its concentration, and the soaking duration are key factors influencing the treatment efficiency. However, the use of strong acids such as HCl and H_2SO_4 may introduce harmful ions (e.g., Cl^- and SO_4^{2-}), which can be detrimental to RCA, and improper disposal of acidic waste solutions can lead to environmental pollution.

Therefore, moderate acid concentrations or environmentally friendly weak acids (e.g., acetic acid) are preferred to balance treatment efficacy with sustainability.

(4) Polymer treatment demonstrates a notable enhancement effect on the performance of RA. However, when PVA solution is used, the formation of a hydrophobic film on the aggregate surface may hinder early hydration at the interfacial transition zone (ITZ), resulting in limited or even negative improvement in the early compressive strength of RAC. As the hydrophobic film gradually decomposes in the alkaline cement environment, the hydration process becomes more complete, leading to a significant increase in the later-age compressive strength of RAC.

(5) The carbonation curing technique not only significantly enhances the performance of RA and RAC, but also utilizes CO_2 to achieve strengthening, thereby effectively reducing environmental impact. Numerous factors influence the carbonation process, including the parent concrete strength, aggregate storage time, particle size, moisture content, curing duration, CO_2 concentration, CO_2 pressure, and ambient humidity. In practical applications, these parameters must be carefully controlled to achieve optimal carbonation efficiency and maximized strengthening effects, ensuring both mechanical improvement and sustainability.

(6) Biological strengthening, typically referring to microbially induced calcium carbonate precipitation (MICP), is an eco-friendly and sustainable technique that can effectively enhance the properties of RA as well as the performance of the resulting RAC or RAM. This method promotes $CaCO_3$ deposition within pores and microcracks, improving microstructural compactness and interfacial bonding. However, its practical application requires precise control of key influencing parameters, such as pH, temperature, bacterial concentration, and calcium ion concentration, to ensure stable microbial activity and maximize the strengthening efficiency.

(7) Physical, chemical, and biological strengthening methods improve RA via different pathways and thus differ in practice: physical methods are generally simple and scalable; chemical methods require stricter control of reagents and experimental conditions and may increase environmental and safety burdens; biological methods are milder and sustainability-oriented but often slower and more sensitive to process stability and scale-up. Therefore, selection should consider not only performance gains but also treatment cost, energy consumption, production cycle, environmental burden, and industrial feasibility.

7.2. Overlook

(1) This study mainly reviews the effects of various individual strengthening methods on the performance of RA and their corresponding RAC or RAM, while only briefly addressing some combined strengthening approaches. In practical engineering applications, synergistic modification strategies that integrate two or more methods are more commonly adopted, such as: acid immersion–mechanical grinding, acid immersion–silicate impregnation, and mechanical grinding–biological deposition. Future research should further explore and experimentally verify the synergistic mechanisms and modification efficiency of these composite approaches, while also assessing their energy consumption, efficiency, and environmental compatibility.

(2) Despite extensive research on RA reinforcement, there are gaps in the study of durability (e.g., freeze–thaw, chloride ion permeability), life cycle assessments (including environmental and economic impacts), and pilot-scale validation. Future research should address these gaps to provide solid theoretical and data support for large-scale application.

(3) While laboratory studies have made progress with various reinforcement methods, pilot-scale verification is crucial for industrial application. Future efforts should focus on enhancing collaboration between academia and industry to ensure the stability, economic feasibility, and operability of technologies, bridging the gap between laboratory results and real-world applications.

(4) Carbonation curing and biological deposition show great promise as environmentally friendly reinforcement techniques. However, their large-scale application is currently limited by technical constraints, high costs, and low process efficiency. Future research should focus on developing low-energy, high-efficiency, renewable resource-based treatment methods. These methods should not only improve mechanical properties and durability but also consider environmental impacts and potential human health effects, contributing to the development of low-carbon construction materials and a circular economy.

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References

1. Sun, L.C.; Yu, L.; Liu, B. Study on mechanical properties of lightweight and high-ductility geopolymer prepared from recycled concrete powder. *New Build. Mater.* **2025**, *52*, 36–41. (In Chinese)
2. Ding, Y.H.; Wu, J.; Xu, P.; Zhang, X.G.; Fan, Y.H. Treatment methods for the quality improvement of recycled concrete aggregate (RCA)—A review. *J. Wuhan Univ. Technol.-Mater. Sci. Ed.* **2021**, *36*, 77–92. [CrossRef]
3. Zhang, H.R.; Zhao, Y.X. Integrated interface parameters of recycled aggregate concrete. *Constr. Build. Mater.* **2015**, *101*, 861–877. [CrossRef]
4. Silva, R.V.; de Brito, J.; Dhir, R.K. Properties and composition of recycled aggregates from construction and demolition waste suitable for concrete production. *Constr. Build. Mater.* **2014**, *65*, 201–217. [CrossRef]
5. Wang, B.; Yan, L.; Fu, Q.; Kasal, B. A comprehensive review on recycled aggregate and recycled aggregate concrete. *Resour. Conserv. Recycl.* **2021**, *171*, 105565. [CrossRef]
6. McNeil, K.; Kang, T.H.K. Recycled concrete aggregates: A review. *Int. J. Concr. Struct. Mater.* **2013**, *7*, 61–69. [CrossRef]
7. Akbarnezhad, A.; Ong, K.C.G.; Zhang, M.H.; Tam, C.T. Acid treatment technique for determining the mortar content of recycled concrete aggregates. *J. Test. Eval.* **2013**, *41*, 441–450. [CrossRef]
8. Limbachiya, M.C. Recycled aggregates: Production, properties and value-added sustainable applications. *J. Wuhan Univ. Technol.-Mater. Sci. Ed.* **2010**, *25*, 1011–1016. [CrossRef]
9. Xiao, J.Z.; Li, W.G.; Sun, Z.H.; Lange, D.A.; Shah, S.P. Properties of interfacial transition zones in recycled aggregate concrete tested by nanoindentation. *Cem. Concr. Compos.* **2013**, *37*, 276–292. [CrossRef]
10. Su, Y.Q.; Yao, Y.C.; Wang, Y.; Zhao, X.; Li, L.; Zhang, J. Modification of recycled concrete aggregate and its use in concrete: An overview of research progress. *Materials* **2023**, *16*, 7144. [CrossRef]
11. Zhen, T. Strengthening method of waste concrete aggregate. *Adv. Res. Teach.* **2024**, *25*, 21–28. [CrossRef]

12. Liu, T.; Yan, X.H.; Zhang, B. Study on the properties and strengthening treatment of recycled aggregates. *J. Phys. Conf. Ser.* **2025**, *2941*, 012031. [CrossRef]
13. Oikonomopoulou, K.; Ioannou, S.; Savva, P.; Spanou, M.; Nicolaides, D.; Petrou, M.F. Effect of mechanically treated recycled aggregates on the long term mechanical properties and durability of concrete. *Materials* **2022**, *15*, 2871. [CrossRef]
14. Ogawa, H.; Nawa, T. Improving the quality of recycled fine aggregate by selective removal of brittle defects. *J. Adv. Concr. Technol.* **2012**, *10*, 395–410. [CrossRef]
15. Noguchi, T.; Kitagaki, R.; Tsujino, M. Minimizing Environmental Impact and Maximizing Performance in Concrete Recycling. *Struct. Concr.* **2011**, *12*, 36–46. [CrossRef]
16. Wang, C.Q.; Cheng, L.X.; Ying, Y.; Yang, F.; Zhang, Y.Q. Utilization of all components of waste concrete: Recycled aggregate strengthening, recycled fine powder activity, composite recycled concrete and life cycle assessment. *J. Build. Eng.* **2024**, *82*, 108255. [CrossRef]
17. Forero, J.A.; de Brito, J.; Evangelista, L.; Pereira Claudio, H.F. Mechanical and fracture properties of concrete with recycled concrete aggregates treated with acids and addition of aluminium sulphate. *Constr. Build. Mater.* **2024**, *447*, 137947. [CrossRef]
18. Peiris, D.; Gunasekara, C.; Law, D.W.; Patrisia, Y.; Tam, V.W.Y.; Setunge, S. Impact of treatment methods on recycled concrete aggregate performance: A comprehensive review. *Environ. Sci. Pollut. Res.* **2025**, *32*, 14405–14438. [CrossRef]
19. Bastos, D.; Farinha, C.B.; Pederneiras, C.M.; Veiga, R.; Bogas, J.A.; Gomes, R.I.; Silva, A.S. Towards industrial implementation: Experimental campaign based on variations in temperature, humidity, and CO_2 concentration in forced carbonation reactions of recycled aggregates. *Appl. Sci.* **2025**, *15*, 5005. [CrossRef]
20. Sharma, H.; Ashish, D.K.; Sharma, S.K. Development of low-carbon recycled aggregate concrete using carbonation treatment and alccofine. *Energy Ecol. Environ.* **2024**, *9*, 230–240. [CrossRef]
21. Luo, M.; Zhao, Y.; Ji, A.; Ding, Z. Enhancing recycled aggregates quality through biological deposition treatment. *J. Build. Eng.* **2025**, *100*, 111681. [CrossRef]
22. Wang, R.X.; Jin, P.; Ding, Z.C.; Zhang, W. Surface modification of recycled coarse aggregate based on Microbial Induced Carbonate Precipitation. *J. Clean. Prod.* **2021**, *328*, 129537. [CrossRef]
23. Tam, V.W.Y.; Soomro, M.; Evangelista, A.C.J. Quality improvement of recycled concrete aggregate by removal of residual mortar: A comprehensive review of approaches adopted. *Constr. Build. Mater.* **2021**, *288*, 123066. [CrossRef]
24. Ouyang, K.; Liu, J.H.; Liu, S.H.; Song, B.Q.; Guo, H.; Li, G.S.; Shi, C.J. Influence of pre-treatment methods for recycled concrete aggregate on the performance of recycled concrete: A review. *Resour. Conserv. Recycl.* **2023**, *188*, 106717. [CrossRef]
25. Santos, W.F.; Quattrone, M.; John, V.M.; Angulo, S.C. Roughness, wettability and water absorption of water repellent treated recycled aggregates. *Constr. Build. Mater.* **2017**, *146*, 502–513. [CrossRef]
26. Pu, Y.H.; Li, L.; Wang, Q.Y.; Shi, X.S.; Luan, C.C.; Zhang, G.M.; Fu, L.; El-Fatah Abomohra, A. Accelerated carbonation technology for enhanced treatment of recycled concrete aggregates: A state-of-the-art review. *Constr. Build. Mater.* **2021**, *282*, 122671. [CrossRef]
27. Wu, C.R.; Hong, Z.Q.; Zhang, J.L.; Kou, S.C. Pore size distribution and ITZ performance of mortars prepared with different bio-deposition approaches for the treatment of recycled concrete aggregate. *Cem. Concr. Compos.* **2020**, *111*, 103631. [CrossRef]
28. Ménard, Y.; Bru, K.; Touzé, S.; Lemoign, A.; Poirier, J.E.; Ruffie, G.; Bonnaudin, F.; Von Der Weid, F. Innovative process routes for a high-quality concrete recycling. *Waste Manag.* **2013**, *33*, 1561–1565. [CrossRef]
29. Everaert, M.; Stein, R.; Michaux, S.; Goovaerts, V.; Groffils, C.; Delvoie, S.; Zhao, Z.; Snellings, R.; Nielsen, P.; Broos, K. Microwave radiation as a pre-treatment for standard and innovative fragmentation techniques in concrete recycling. *Materials* **2019**, *12*, 488. [CrossRef]
30. Touzé, S.; Bru, K.; Ménard, Y.; Soret, L.; Lanos, C.; Sornay, P. Electrical fragmentation applied to the recycling of concrete waste–Effect on aggregate liberation. *Int. J. Miner. Process.* **2017**, *158*, 68–75. [CrossRef]
31. Arifi, E.; Ishimatsu, K.; Iizasa, S.; Namihira, T.; Sakamoto, H.; Tachi, Y.; Kato, H.; Shigeishi, M. Reduction of contaminated concrete waste by recycling aggregate with the aid of pulsed power discharge. *Constr. Build. Mater.* **2014**, *67*, 192–196. [CrossRef]
32. Zhang, X.G.; Wang, C.H.; Wang, J.B.; Liu, X.Y.; Huang, Y.J.; Wang, L.Y.; Ding, Y.H. Experimental study on the compressive fatigue performance of nano-silica modified recycled aggregate concrete. *Constr. Build. Mater.* **2024**, *447*, 138161. [CrossRef]
33. Zhang, X.G.; Li, M.B.; Wang, C.H.; Li, Y.L.; Fan, Y.H.; Yang, J.Y.; Liu, C.; Li, W. Multi-parameter analysis of nano-SiO_2 modified recycled aggregate concrete: Fatigue damage and microscopic mechanisms. *Structures* **2025**, *79*, 109414. [CrossRef]
34. Zhang, X.G.; Wang, L.Y.; Shen, Y.C.; Liu, J.F.; Fan, Y.H. Analysis of flexural fatigue damage and micro-mechanisms of nano-SiO2 modified recycled aggregate concrete. *Constr. Build. Mater.* **2025**, *487*, 142004. [CrossRef]
35. Zhao, Z.H.; Wang, S.D.; Lu, L.C.; Gong, C. Evaluation of pre-coated recycled aggregate for concrete and mortar. *Constr. Build. Mater.* **2013**, *43*, 191–196. [CrossRef]
36. Junak, J.; Sicakova, A. Effect of surface modifications of recycled concrete aggregate on concrete properties. *Buildings* **2017**, *8*, 2. [CrossRef]

37. Hentges, T.I.; Kautzmann, V.O.; Angulo, S.C.; Kazmierczak, C.d.S.; Mancio, M.; Sander, A.; Kulakowski, M.P. Comparative study of porous recycled concrete aggregates treated with pozzolanic slurry or carbonation and resulting recycled concrete properties. *Int. J. Civ. Eng.* **2023**, *21*, 1965–1984. [CrossRef]
38. Lee, C.H.; Du, J.C.; Shen, D.H. Evaluation of pre-coated recycled concrete aggregate for hot mix asphalt. *Constr. Build. Mater.* **2012**, *28*, 66–71. [CrossRef]
39. Zhang, P.; Qin, Z.; Gao, Z.; Wang, F.; Lai, C. Research progress on impact resistance of fiber-reinforced concrete—A review. *J. Build. Eng.* **2025**, *112*, 113982. [CrossRef]
40. Zhang, X.G.; Zhu, Y.N.; Shen, Y.C.; Zhou, G.Q.; Huang, Y.J.; Li, M.B.; Xu, P.; Ding, Y.H. Compressive mechanical performance and microscopic mechanism of basalt fiber-reinforced recycled aggregate concrete after elevated temperature exposure. *J. Build. Eng.* **2024**, *96*, 110647. [CrossRef]
41. Zhang, X.G.; Zhu, Y.N.; Fan, Y.H.; Zhou, G.Q.; Huang, Y.J.; Li, M.B.; Shen, W.L. Experimental study on impact resistance and dynamic constitutive relation of steel fiber reinforced recycled aggregate concrete. *Constr. Build. Mater.* **2024**, *449*, 138396. [CrossRef]
42. Zhang, X.G.; Li, Y.L.; Fan, Y.H.; Zhou, G.Q.; Huang, Y.J.; Xu, P.; Ding, Y.H. Analysis on the impact resistance of steel fiber reinforced recycled aggregate concrete. *Structures* **2025**, *75*, 108599. [CrossRef]
43. Zhang, X.; Li, M.; Niu, J.; Fan, Y.; Liu, J. Dynamic mechanical properties of steel-polypropylene hybrid fiber reinforced concrete. *Constr. Build. Mater.* **2025**, *485*, 141927. [CrossRef]
44. Yao, X.; Pei, Z.; Zheng, H.; Guan, Q.; Wang, F.; Wang, S.; Ji, Y. Review of mechanical and temperature properties of fiber reinforced recycled aggregate concrete. *Buildings* **2022**, *12*, 1224. [CrossRef]
45. Feng, C.; Cui, B.; Huang, Y.; Guo, H.; Zhang, W.; Zhu, J. Enhancement technologies of recycled aggregate–Enhancement mechanism, influencing factors, improvement effects, technical difficulties, life cycle assessment. *Constr. Build. Mater.* **2022**, *317*, 126168. [CrossRef]
46. Li, Z.; Azman, M.N.A.; Jaya, R.P. Review of Research on Coarse Aggregate Reinforcement of Recycled Concrete. *Construction* **2023**, *3*, 135–141. [CrossRef]
47. Sui, Y.; Mueller, A. Development of thermo-mechanical treatment for recycling of used concrete. *Mater. Struct.* **2012**, *45*, 1487–1495. [CrossRef]
48. Pawluczuk, E.; Kalinowska-Wichrowska, K.; Bołtryk, M.; Jiménez, J.R.; Fernández, J.M. The influence of heat and mechanical treatment of concrete rubble on the properties of recycled aggregate concrete. *Materials* **2019**, *12*, 367. [CrossRef]
49. Liang, R.; Yu, J.; Qin, Y.J. Review on the research of recycled aggregate from waste concrete. *Concrete* **2013**, *5*, 93–96. (In Chinese)
50. Li, Q.Y.; Li, Y.X.; Zhu, C.J.; Zhang, Y.H.; Wang, Z.Z. Study on strengthening technology of recycled concrete aggregate. *Concrete* **2006**, *1*, 4. (In Chinese)
51. Huang, K.; Ding, T.; Xiao, J.; Singh, A. Modification on recycled aggregates and its influence on recycled concrete. In Proceedings of the IOP Conference Series: Earth and Environmental Science, Malang City, Indonesia, 12–13 March 2019; Volume 323, p. 012136. [CrossRef]
52. Gong, Y.F.; Chen, P.; Lin, Y.J.; Zhao, X.L.; Wang, Z.Z. Improvement of recycled aggregate properties through a combined method of mechanical grinding and microbial-induced carbonate precipitation. *Constr. Build. Mater.* **2022**, *342*, 128093. [CrossRef]
53. Pepe, M.; Toledo Filho, R.D.; Koenders, E.A.B.; Martinelli, E. Alternative processing procedures for recycled aggregates in structural concrete. *Constr. Build. Mater.* **2014**, *69*, 124–132. [CrossRef]
54. Dilbas, H.; Çakır, Ö.; Atiş, C.D. Experimental investigation on properties of recycled aggregate concrete with optimized ball milling method. *Constr. Build. Mater.* **2019**, *212*, 716–726. [CrossRef]
55. Verma, A.; Babu, V.S.; Arunachalam, S. Characterization of recycled aggregate by the combined method: Acid soaking and mechanical grinding technique. *Mater. Today Proc.* **2022**, *49*, 230–238. [CrossRef]
56. Verma, A.; Babu, V.S.; Arunachalam, S. Influence of acetic acid soaking and mechanical grinding treatment on the properties of treated recycled aggregate concrete. *J. Mater. Cycles Waste Manag.* **2022**, *24*, 877–899. [CrossRef]
57. Goliya, R.K.; Babu, V.S. Performance evaluation of concrete made with double-processed recycled aggregate (DPRA): Mechanical grinding and silica fume impregnation technique. *J. Mater. Cycles Waste Manag.* **2023**, *25*, 1050–1068. [CrossRef]
58. Purushothaman, R.; Amirthavalli, R.R.; Karan, L. Influence of treatment methods on the strength and performance characteristics of recycled aggregate concrete. *J. Mater. Civ. Eng.* **2015**, *27*, 04014168. [CrossRef]
59. Pandurangan, K.; Dayanithy, A.; Prakash, S.O. Influence of treatment methods on the bond strength of recycled aggregate concrete. *Constr. Build. Mater.* **2016**, *120*, 212–221. [CrossRef]
60. Dimitriou, G.; Savva, P.; Petrou, M.F. Enhancing mechanical and durability properties of recycled aggregate concrete. *Constr. Build. Mater.* **2018**, *158*, 228–235. [CrossRef]
61. Pedro, D.; De Brito, J.; Evangelista, L. Performance of concrete made with aggregates recycled from precasting industry waste: Influence of the crushing process. *Mater. Struct.* **2015**, *48*, 3965–3978. [CrossRef]

62. Ma, A.W.; Zhang, J.G.; Wang, X.T.; Meng, Q.; Liu, Y.; Zhou, A. A practical enhancing method of recycled concrete aggregates via combination of mechanical grinding and microbial consortia-spraying: Preliminary tests. *J. Clean. Prod.* **2024**, *472*, 143530. [CrossRef]
63. Mardani, A.; Bui, N.K.; Noguchi, T. Hybrid environmentally friendly method for RCA concrete quality improvement. *Int. J. Concr. Struct. Mater.* **2024**, *18*, 29. [CrossRef]
64. Bru, K.; Touzé, S.; Bourgeois, F.; Lippiatt, N.; Ménard, Y. Assessment of a microwave-assisted recycling process for the recovery of high-quality aggregates from concrete waste. *Int. J. Miner. Process.* **2014**, *126*, 90–98. [CrossRef]
65. Ong, K.C.G.; Akbarnezhad, A. *Microwave-Assisted Concrete Technology: Production, Demolition and Recycling*; CRC Press: Boca Raton, FL, USA, 2014. [CrossRef]
66. Xiao, Y.H.; Shao, Z.S. Numerical analysis of mortar-aggregate separation induced by microwave heating. *Int. J. Therm. Sci.* **2023**, *184*, 107957. [CrossRef]
67. Sheng, Y.P.; Huan, X.; Hu, P.Z.; Li, L.; Abdulakeem, A.; Ye, Z.; Wang, L.; Yin, Y. Stripping of aggregate from mortar in waste concrete heated by microwave: Mechanisms of differential-temperature stress and vapor expansion pressure. *J. Traffic Transp. Eng.* **2024**, *11*, 538–558. [CrossRef]
68. Lv, T.; Xu, L.; Wang, J.J.; Zhang, Q.; Ran, B.; Huang, R.; Tang, H.; Wang, D. Review on physical performance, modification mechanisms, carbon emissions and economic costs of recycled aggregates modified with physical enhancement technologies. *J. Environ. Manag.* **2024**, *357*, 120713. [CrossRef] [PubMed]
69. Tsujino, M.; Noguchi, T.; Kitagaki, R.; Nagai, H. Completely recyclable concrete of aggregate-recovery type by a new technique using aggregate coating. *Archit. Inst. Jpn.* **2010**, *75*, 17–24. [CrossRef]
70. Wei, W.; Shao, Z.S.; Chen, W.W.; Zhang, P.J.; Yuan, Y. A fully coupled electromagnetic irradiation, heat and mass transfer model of microwave heating on concrete. *IEEE Access* **2020**, *9*, 1575–1589. [CrossRef]
71. Li, J.S.; Xiao, H.N.; Zhou, Y. Influence of coating recycled aggregate surface with pozzolanic powder on properties of recycled aggregate concrete. *Constr. Build. Mater.* **2009**, *23*, 1287–1291. [CrossRef]
72. Akbarnezhad, A.; Ong, K.C.G.; Zhang, M.H.; Tam, C.T.; Foo, T.W.J. Microwave-assisted beneficiation of recycled concrete aggregates. *Constr. Build. Mater.* **2011**, *25*, 3469–3479. [CrossRef]
73. Xiao, J.Z.; Wu, L.; Fan, Y.H. Experimental study on modification of recycled coarse aggregate by microwave heating. *Concrete* **2012**, 55–57. (In Chinese)
74. Chen, W.W.; Shao, Z.S.; Wei, W.; Zhang, P.; Hong, Y.K. Properties of concrete incorporating microwave treated coarse aggregate: An experimental study. In *Structures*; Elsevier: Amsterdam, The Netherlands, 2021; Volume 33, pp. 693–702. [CrossRef]
75. Zhao, H.X.; Sun, Y. Experimental study on modification of recycled aggregate by microwave heating. *Bull. Chin. Ceram. Soc.* **2019**, *38*, 3518–3523. (In Chinese)
76. Xiao, Y.H.; Shao, Z.S.; Wei, W.; Han, Y.; Jiang, Y.; Chai, S.; Chen, X.; Zong, Z. Effect of microwave pretreatment on mechanical behavior of concrete and aggregate recovery. *Constr. Build. Mater.* **2023**, *387*, 131647. [CrossRef]
77. Tam, V.W.Y.; Tam, C.M.; Le, K.N. Removal of cement mortar remains from recycled aggregate using pre-soaking approaches. *Resour. Conserv. Recycl.* **2007**, *50*, 82–101. [CrossRef]
78. Wang, L.; Wang, J.L.; Qian, X.; Chen, P.; Xu, Y.; Guo, J. An environmentally friendly method to improve the quality of recycled concrete aggregates. *Constr. Build. Mater.* **2017**, *144*, 432–441. [CrossRef]
79. Saravanakumar, P.; Abhiram, K.; Manoj, B. Properties of treated recycled aggregates and its influence on concrete strength characteristics. *Constr. Build. Mater.* **2016**, *111*, 611–617. [CrossRef]
80. Kim, H.S.; Kim, B.; Kim, K.S.; Kim, J.M. Quality improvement of recycled aggregates using the acid treatment method and the strength characteristics of the resulting mortar. *J. Mater. Cycles Waste Manag.* **2017**, *19*, 968–976. [CrossRef]
81. Kim, Y.; Hanif, A.; Kazmi, S.M.S.; Munir, M.J.; Park, C. Properties enhancement of recycled aggregate concrete through pretreatment of coarse aggregates–Comparative assessment of assorted techniques. *J. Clean. Prod.* **2018**, *191*, 339–349. [CrossRef]
82. Neville, A.M. *Properties of Concrete*; Longman: London, UK, 1995. Available online: https://archive.org/details/propertiesofconc0000nevi_4edi (accessed on 9 July 2025).
83. Mehta, P.K. Mechanism of sulfate attack on portland cement concrete—Another look. *Cem. Concr. Res.* **1983**, *13*, 401–406. [CrossRef]
84. Ismail, S.; Ramli, M. Engineering properties of treated recycled concrete aggregate (RCA) for structural applications. *Constr. Build. Mater.* **2013**, *44*, 464–476. [CrossRef]
85. Shi, C.J.; Li, Y.K.; Zhang, J.K.; Li, W.G.; Chong, L.L.; Xie, Z.B. Performance enhancement of recycled concrete aggregate–A review. *J. Clean. Prod.* **2016**, *112*, 466–472. [CrossRef]
86. Chauhan, B.L.; Singh, G.J. Sustainable development of recycled concrete aggregate through optimized acid-mechanical treatment: A simplified approach. *Constr. Build. Mater.* **2023**, *399*, 132559. [CrossRef]
87. Chen, K.; Zhu, Z.; Xue, T.; Zhang, H.; Wang, A.; He, R.; Yang, H.; Wang, Y. Enhancement treatment of recycled concrete aggregate. *Front. Built Environ.* **2021**, *7*, 739148. [CrossRef]

88. Kou, S.C.; Poon, C.S. Properties of concrete prepared with PVA-impregnated recycled concrete aggregates. *Cem. Concr. Compos.* **2010**, *32*, 649–654. [CrossRef]
89. Qiu, J.; Zhang, Y.; Qin, Q.; Xiao, Z.; Lei, T.; Li, L. Study on mechanical properties and microscopic mechanism of PVA-modified recycled brick aggregate concrete. *Sustainability* **2024**, *16*, 1292. [CrossRef]
90. Spaeth, V.; Djerbi Tegguer, A. Polymer based treatments applied on recycled concrete aggregates. *Adv. Mater. Res.* **2013**, *687*, 514–519. [CrossRef]
91. Xu, J. Research on Modification and Application of Recycled Concrete Aggregate. Master's Thesis, Anhui University of Science and Technology, Huainan, China, 2017. (In Chinese)
92. Ohama, Y. Polymer-based admixtures. *Cem. Concr. Compos.* **1998**, *20*, 189–212. [CrossRef]
93. Su, Z.; Bijen, J.; Larbi, J.A. Influence of polymer modification on the hydration of portland cement. *Cem. Concr. Res.* **1991**, *21*, 242–250. [CrossRef]
94. Yaowarat, T.; Horpibulsuk, S.; Arulrajah, A.; Mirzababaei, M.; Rashid, A.S.A. Compressive and flexural strength of polyvinyl alcohol–modified pavement concrete using recycled concrete aggregates. *J. Mater. Civ. Eng.* **2018**, *30*, 04018046. [CrossRef]
95. Ho, H.L.; Huang, R.; Lin, W.T.; Cheng, A.; Chang, J.W.C.; Yang, C.H.; Wang, C.C.; Lai, J.S. Pore-structures and durability of concrete containing pre-coated fine recycled mixed aggregates using pozzolan and polyvinyl alcohol materials. *Constr. Build. Mater.* **2018**, *160*, 278–292. [CrossRef]
96. Yaowarat, T.; Horpibulsuk, S.; Arulrajah, A.; Mohammadinia, A.; Chinkulkijniwat, A. Recycled concrete aggregate modified with polyvinyl alcohol and fly ash for concrete pavement applications. *J. Mater. Civ. Eng.* **2019**, *31*, 04019103. [CrossRef]
97. Spaeth, V.; Tegguer, A.D. Improvement of recycled concrete aggregate properties by polymer treatments. *Int. J. Sustain. Built Environ.* **2013**, *2*, 143–152. [CrossRef]
98. Zhao, T.; Wittmann, F.H.; Jiang, R.; Li, W. Application of silane-based compounds for the production of integral water repellent concrete. In Proceedings of the 6th International Conference on WR Treatment of Building Materials, HVI, Rome, Italy, 12–13 May 2011; pp. 137–144.
99. Zhu, Y.G.; Kou, S.C.; Poon, C.S.; Dai, J.; Li, Q.Y. Influence of silane-based water repellent on the durability properties of recycled aggregate concrete. *Cem. Concr. Compos.* **2013**, *35*, 32–38. [CrossRef]
100. Yang, N.; Wang, C.G.; Zhao, M.X. Study on strengthening technology of recycled aggregate. *New Build. Mater.* **2011**, *38*, 45–47. (In Chinese)
101. Liu, T.J.; Wang, Z.Z.; Zou, D.J.; Zhou, A.; Du, J. Strength enhancement of recycled aggregate pervious concrete using a cement paste redistribution method. *Cem. Concr. Res.* **2019**, *122*, 72–82. [CrossRef]
102. Weng, Z. Experimental Study on the Influence of Strengthening Pretreatment of Recycled Coarse Aggregate on the Mesostructure of High-Performance Recycled Concrete. Master's Thesis, Fuzhou University, Fuzhou, China, 2013. (In Chinese)
103. Zhang, J.K.; Shi, C.J.; Li, Y.K.; Pan, X.; Poon, C.S.; Xie, Z.B. Performance enhancement of recycled concrete aggregates through carbonation. *J. Mater. Civ. Eng.* **2015**, *27*, 04015029. [CrossRef]
104. Luo, S.R.; Ye, S.C.; Xiao, J.Z.; Zheng, J.; Zhu, Y. Carbonated recycled coarse aggregate and uniaxial compressive stress-strain relation of recycled aggregate concrete. *Constr. Build. Mater.* **2018**, *188*, 956–965. [CrossRef]
105. Wu, K.Y.; Luo, S.R.; Zheng, J.L.; Yan, J.; Xiao, J. Influence of carbonation treatment on the properties of multiple interface transition zones and recycled aggregate concrete. *Cem. Concr. Compos.* **2022**, *127*, 104402. [CrossRef]
106. Li, L.; Poon, C.S.; Xiao, J.Z.; Xuan, D. Effect of carbonated recycled coarse aggregate on the dynamic compressive behavior of recycled aggregate concrete. *Constr. Build. Mater.* **2017**, *151*, 52–62. [CrossRef]
107. Ma, J.; Dai, G.; Jiang, F.; Wang, N.; Zhao, Y.; Wang, X. Effect of carbonation treatment on the properties of steel slag aggregate. *Materials* **2023**, *16*, 5768. [CrossRef]
108. Zhong, W.; Wang, P.; Ye, N.; Li, J. Effects of Different Carbonation Treatment Methods for Recycled Concrete Aggregate. *Buildings* **2025**, *15*, 3054. [CrossRef]
109. Song, B.C.; Yan, H.; Cui, H.M.; Liu, J.K.; Qin, H.T.; Wang, J. Effect of carbonation on chloride ion penetration resistance of CO_2-strengthened recycled aggregate concrete. *Mater. Rev.* **2023**, *37*, 147–150. (In Chinese)
110. Pico-Cortés, C.; Villagrán-Zaccardi, Y. Unraveling the Interplay of Physical-Chemical Factors Impacting the Carbonation Performance of Recycled Aggregate Concrete. *Materials* **2023**, *16*, 5692. [CrossRef]
111. Zhang, J.; Shi, C.; Li, Y.; Pan, X.; Poon, C.S.; Xie, Z. Influence of carbonated recycled concrete aggregate on properties of cement mortar. *Constr. Build. Mater.* **2015**, *98*, 1–7. [CrossRef]
112. Li, L.; Xiao, J.Z.; Xuan, D.X.; Poon, C.S. Effect of carbonation of modeled recycled coarse aggregate on the mechanical properties of modeled recycled aggregate concrete. *Cem. Concr. Compos.* **2018**, *89*, 169–180. [CrossRef]
113. Xuan, D.X.; Zhan, B.J.; Poon, C.S. Durability of recycled aggregate concrete prepared with carbonated recycled concrete aggregates. *Cem. Concr. Compos.* **2017**, *84*, 214–221. [CrossRef]
114. Xuan, D.X.; Zhan, B.J.; Poon, C.S. Assessment of mechanical properties of concrete incorporating carbonated recycled concrete aggregates. *Cem. Concr. Compos.* **2016**, *65*, 67–74. [CrossRef]

115. Tam, V.W.Y.; Butera, A.; Le, K.N. Carbon-conditioned recycled aggregate in concrete production. *J. Clean. Prod.* **2016**, *133*, 672–680. [CrossRef]
116. Zhan, B.J.; Xuan, D.X.; Poon, C.S.; Shi, C.J. Effect of curing parameters on CO_2 curing of concrete blocks containing recycled aggregates. *Cem. Concr. Compos.* **2016**, *71*, 122–130. [CrossRef]
117. Zhan, M.M.; Pan, G.H.; Wang, Y.P.; Zhang, Z.Y.; Li, J.; Shi, C.J. Effect of presoak-accelerated carbonation factors on enhancing recycled aggregate mortars. *Mag. Concr. Res.* **2017**, *69*, 838–849. [CrossRef]
118. Li, Y.; Fu, T.H.; Wang, R.J.; Li, Y. An assessment of microcracks in the interfacial transition zone of recycled concrete aggregates cured by CO_2. *Constr. Build. Mater.* **2020**, *236*, 117543. [CrossRef]
119. Zhan, B.J.; Poon, C.S.; Liu, Q.; Kou, S.; Shi, C. Experimental study on CO_2 curing for enhancement of recycled aggregate properties. *Constr. Build. Mater.* **2014**, *67*, 3–7. [CrossRef]
120. Lin, M.; Li, X.; Wei, M.; Xie, Q. Experimental Study on Carbonization and Strengthening Performance of Recycled Aggregate. *Buildings* **2025**, *15*, 2309. [CrossRef]
121. Zhan, B.J.; Xuan, D.X.; Poon, C.S. Enhancement of recycled aggregate properties by accelerated CO_2 curing coupled with limewater soaking process. *Cem. Concr. Compos.* **2018**, *89*, 230–237. [CrossRef]
122. De Muynck, W.; De Belie, N.; Verstraete, W. Microbial carbonate precipitation in construction materials: A review. *Ecol. Eng.* **2010**, *36*, 118–136. [CrossRef]
123. Gollapudi, U.K.; Knutson, C.L.; Bang, S.S.; Islam, M.R. A new method for controlling leaching through permeable channels. *Chemosphere* **1995**, *30*, 695–705. [CrossRef]
124. Vijay, K.; Murmu, M.; Deo, S.V. Bacteria based self healing concrete—A review. *Constr. Build. Mater.* **2017**, *152*, 1008–1014. [CrossRef]
125. Seifan, M.; Berenjian, A. Application of microbially induced calcium carbonate precipitation in designing bio self-healing concrete. *World J. Microbiol. Biotechnol.* **2018**, *34*, 168. [CrossRef] [PubMed]
126. Wu, C.R.; Zhu, Y.G.; Zhang, X.T.; Kou, S.C. Improving the properties of recycled concrete aggregate with bio-deposition approach. *Cem. Concr. Compos.* **2018**, *94*, 248–254. [CrossRef]
127. Joshi, S.; Goyal, S.; Mukherjee, A.; Reddy, M.S. Microbial healing of cracks in concrete: A review. *J. Ind. Microbiol. Biotechnol.* **2017**, *44*, 1511–1525. [CrossRef]
128. Sahoo, K.K.; Arakha, M.; Sarkar, P.; Davis, P.; Jha, S. Enhancement of properties of recycled coarse aggregate concrete using bacteria. *Int. J. Smart Nano Mater.* **2016**, *7*, 22–38. [CrossRef]
129. Grabiec, A.M.; Klama, J.; Zawal, D.; Krupa, D. Modification of recycled concrete aggregate by calcium carbonate biodeposition. *Constr. Build. Mater.* **2012**, *34*, 145–150. [CrossRef]
130. García-González, J.; Rodríguez-Robles, D.; Wang, J.; De Belie, N.; del Pozo, J.M.M.; Guerra-Romero, M.I.; Juan-Valdes, A. Quality improvement of mixed and ceramic recycled aggregates by biodeposition of calcium carbonate. *Constr. Build. Mater.* **2017**, *154*, 1015–1023. [CrossRef]
131. Siddique, R.; Chahal, N.K. Effect of ureolytic bacteria on concrete properties. *Constr. Build. Mater.* **2011**, *25*, 3791–3801. [CrossRef]
132. Pan, Z.Y.; Li, G.Y.; Hong, C.Y.; Kuang, H.L.; Yu, Y.; Feng, F.X.; Liu, D.M.; Du, H. Modified recycled concrete aggregates for asphalt mixture using microbial calcite precipitation. *RSC Adv.* **2015**, *5*, 34854–34863. [CrossRef]
133. Wang, J.; Pang, S.; Zhan, X.; Wei, W.; Li, X.; Wang, L.; Huang, X.; Zhang, L. Improving Recycled Concrete Aggregate Performance via Microbial-Induced Calcium Carbonate Precipitation: Effects of Bacterial Strains and Mineralization Conditions. *Buildings* **2025**, *15*, 825. [CrossRef]
134. Wong, L.S. Microbial cementation of ureolytic bacteria from the genus *Bacillus*: A review of the bacterial application on cement-based materials for cleaner production. *J. Clean. Prod.* **2015**, *93*, 5–17. [CrossRef]
135. Wang, J.Y.; Vandevyvere, B.; Vanhessche, S.; Schoon, J.; Boon, N.; De Belie, N. Microbial carbonate precipitation for the improvement of quality of recycled aggregates. *J. Clean. Prod.* **2017**, *156*, 355–366. [CrossRef]
136. Feng, Z.Y.; Zhao, Y.X.; Zeng, W.L.; Lu, Z.M.; Shah, S.P. Using microbial carbonate precipitation to improve the properties of recycled fine aggregate and mortar. *Constr. Build. Mater.* **2020**, *230*, 116949. [CrossRef]
137. Zhang, J.; Wang, C.; Wang, Z. Factors affecting the physical properties of microbial induced calcium carbonate precipitation (MICP) enhanced recycled aggregates. *Buildings* **2024**, *14*, 2851. [CrossRef]
138. Qiu, J.S.; Tng, D.Q.S.; Yang, E.H. Surface treatment of recycled concrete aggregates through microbial carbonate precipitation. *Constr. Build. Mater.* **2014**, *57*, 144–150. [CrossRef]
139. Zhan, M.M.; Pan, G.H.; Wang, Y.P.; Fu, M.; Lu, X.J. Recycled aggregate mortar enhanced by microbial calcite precipitation. *Mag. Concr. Res.* **2020**, *72*, 622–633. [CrossRef]
140. Pu, Y.H.; Li, L.; Shi, X.S.; Wang, Q.Y.; Abomohra, A. A comparative life cycle assessment on recycled concrete aggregates modified by accelerated carbonation treatment and traditional methods. *Waste Manag.* **2023**, *172*, 235–244. [CrossRef]
141. Raman, J.V.M.; Somiyadevi, P.; Kandasamy, S. Evaluation of Various Treatment Methods for Enhancing the Recycled Aggregate Concrete. *Int. J. Pavement Res. Technol.* **2024**, 1–19. [CrossRef]

142. Wei, W.; Shao, Z.S.; Qiao, R.J.; Chen, W.W.; Zhang, P.J.; Cheng, J.X. Workability and mechanical properties of microwave heating for recovering high quality aggregate from concrete. *Constr. Build. Mater.* **2021**, *276*, 122237. [CrossRef]
143. Buttress, A.; Jones, A.; Kingman, S. Microwave processing of cement and concrete materials–towards an industrial reality? *Cem. Concr. Res.* **2015**, *68*, 112–123. [CrossRef]
144. Makul, N.; Rattanadecho, P.; Agrawal, D.K. Applications of microwave energy in cement and concrete–a review. *Renew. Sustain. Energy Rev.* **2014**, *37*, 715–733. [CrossRef]
145. Peiris, D.; Patrisia, Y.; Gunasekara, C.; Law, D.W.; Tam, V.W.Y.; Setunge, S. Environmental impact of recycled aggregate treatment methods using life-cycle assessment and cost analysis. *Int. J. Life Cycle Assess.* **2025**, *30*, 2573–2592. [CrossRef]
146. Ouyang, K.; Shi, C.J.; Chu, H.Q.; Guo, H.; Song, B.X.; Ding, Y.H.; Guan, X.M.; Zhu, J.P.; Zhang, H.B.; Wang, Y.L.; et al. An overview on the efficiency of different pretreatment techniques for recycled concrete aggregate. *J. Clean. Prod.* **2020**, *263*, 121264. [CrossRef]
147. Li, L.; Ziyabek, N.; Jiang, Y.; Xiao, J.Z.; Poon, C.S. Effect of carbonation duration on properties of recycled aggregate concrete. *Case Stud. Constr. Mater.* **2023**, *19*, e02640. [CrossRef]
148. Torrenti, J.M.; Amiri, O.; Barnes-Davin, L.; Bougrain, F.; Braymand, S.; Cazacliu, B.; Colin, J.; Cudeville, A.; Dangla, P.; Djerbi, A.; et al. The FastCarb project: Taking advantage of the accelerated carbonation of recycled concrete aggregates. *Case Stud. Constr. Mater.* **2022**, *17*, e01349. [CrossRef]
149. Zhu, Y.G.; Li, Q.Q.; Xu, P.Z.; Wang, X.R.; Kou, S.C. Properties of concrete prepared with recycled aggregates treated by bio-deposition adding oxygen release compound. *Materials* **2019**, *12*, 2147. [CrossRef] [PubMed]
150. Rowell, A.; Ghebrab, T.; Jeter, R. Bacterial treatment of recycled concrete aggregate. *Recycling* **2023**, *8*, 68. [CrossRef]
151. Ahmad, M.A.; Liu, B.; Li, Q.; Adeel, M.; Zhang, J.; Zhou, Y.; Deng, X. Bio-deposition approaches for sustainable execution of recycled aggregates in concretes. *Front. Mater.* **2023**, *10*, 1131673. [CrossRef]

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