buildings

MDPI

Article

Experimental Study on Carbonization and Strengthening Performance of Recycled Aggregate

Mingqiang Lin [1,2,*], Xiang Li [1], Maozhi Wei [1] and Qun Xie [1]

[1] School of Civil Engineering and Architecture, University of Jinan, Jinan 250022, China; 202421201467@stu.ujn.edu.cn (X.L.); maozhi_wei@stu.ujn.edu.cn (M.W.); cea_xieq@ujn.edu.cn (Q.X.)
[2] High-Speed Railway Engineering Technology Research and Development Center, Shandong Railway Investment Holding Group Co., Ltd., Jinan 250102, China
* Correspondence: cea_linmq@ujn.edu.cn

Abstract

In order to address a challenging issue in the recycling of construction debris, the impact of carbonization treatment on the characteristics of recycled aggregates (RCAs) was experimentally examined in this work. Both direct carbonization and carbonization following calcium hydroxide pretreatment were used in the study to assess the impact of carbonization on the physical characteristics of recycled aggregates. According to the findings, carbonization raised the recycled aggregates' apparent density while drastically lowering their porosity and water absorption (by as much as 20–30%). Although the recycled aggregate's crushing index marginally increased with age, its overall physical qualities remained excellent. Pretreatment with calcium hydroxide can improve the physical characteristics of recycled aggregates, further optimize their pore structure, and efficiently encourage the carbonation process. Furthermore, recycled aggregate's crushing index can be considerably decreased and its quality much enhanced by the ultrasonic cavitation treatment. According to the study, the carbonation-treated recycled aggregate's microstructure was denser in the interfacial transition zone and had a stronger link with the cement paste, improving the recycled aggregate concrete's overall performance. XRD, infrared spectral analysis, and SEM scanning were used to determine the increased calcium carbonate content in the recycled aggregate following carbonation treatment as well as its microstructure improvement process. The findings offer fresh concepts for achieving resource efficiency and environmental preservation through the use of recycled aggregates in concrete, as well as theoretical backing for their use.

Keywords: recycled coarse aggregate; carbonization strengthening; calcium hydroxide pretreatment; physical properties

check for updates

Academic Editor: Eugeniusz Koda

Received: 6 March 2025
Revised: 7 April 2025
Accepted: 8 April 2025
Published: 1 July 2025

Citation: Lin, M.; Li, X.; Wei, M.; Xie, Q. Experimental Study on Carbonization and Strengthening Performance of Recycled Aggregate. *Buildings* **2025**, *15*, 2309. https://doi.org/10.3390/buildings15132309

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

With the rapid development of China's economy and the acceleration of urbanization, the construction industry is booming, and the use of construction materials and CO_2 emissions are increasing year by year. Carbon emissions from the building materials industry dominate the construction industry [1]. In 2021, China proposed a "dual-carbon" goal, and since then, people have been increasingly concerned about sustainable development and the reduction of greenhouse gas (GHG) emissions [2]. Concrete production and dismantling generate large amounts of greenhouse gases and construction waste. The current construction industry faces a significant challenge in recycling construction refuse. The

demand for concrete has increased significantly due to the accelerated development of the construction industry. In 2013, China's production of construction waste surpassed 1 billion tons [3]. The 2020 estimate is as high as 1.65 billion tons [4], representing a nearly one-third increase. However, there are two main ways to dispose of this construction waste, one is to use it as backfill material; the other is through burial [5]. Statistics show that up to 3 billion tons of construction waste are landfilled every year [6]. The building sector faces difficulties in recycling and repurposing construction debris as resources. The need for concrete has also increased due to the industry's rapid growth; in 2013, China produced 5 billion cubic meters of concrete, requiring 3.5 billion tons of sand and gravel (70 percent of the total), which resulted in significant resource and ecological issues. The production of recycled aggregates from construction detritus has the potential to conserve 800 million tons of natural sand and gravel annually, reduce the extraction of natural stone by one-third, and conserve 350,000 mu of land [7]. The resource crisis can be resolved through the use of recycled aggregates (RCAs) in the preparation of concrete. Additionally, there are economic and environmental advantages. In the presence of carbon dioxide, the carbonizable materials in recycled aggregates can produce calcium carbonate and silica gel, filling the pores and fractures and enhancing the physical properties. Research has demonstrated that carbonation can effectively sequester CO_2 in the atmosphere and improve the mechanical and durability properties of recycled aggregate concrete. Consequently, the investigation of carbonation in recycled aggregates is of great importance in promoting its application and realizing environmental protection and resource recycling.

In 1946, scholars in the former Soviet Union proposed to recycle recycled aggregate as aggregate and performed the corresponding research [8]; this was followed by Japan since, in 1977, they developed the "Recycled Aggregate and Recycled Concrete Use Specification" as a basis for the establishment of a large number of recycled aggregate recycling plants throughout the country [9]. The Superfund Act enacted in the United States greatly promotes the development of recycled concrete, so the promotion of recycled concrete in the world provides a strong guarantee. Regenerated aggregates, derived from crushing and sieving natural aggregate concrete, comprise mainly regenerated coarse aggregates and the attached hardened cement paste on their surface. The porous nature of the hardened cement paste leads to high water absorption and porosity in the aggregates, reducing their strength. While the water absorption of natural aggregates generally ranges from 1% to 5%, the water absorption of recycled aggregates ranges from 3% to 12% [10]. In 2004, Li Jiabin concluded through tests that the apparent density of recycled aggregates is about 12% lower than that of natural aggregates, and the water absorption is about 20% higher [11]. And in 2014 Kou determined the porosity of 10 mm recycled and natural aggregates, which led to the conclusion that the porosity of recycled aggregates is five times higher than that of natural aggregates [12]. Quan Hongzhu and Zhang Jiufeng [13,14] found that the dry apparent density of recycled coarse aggregate is related to the amount of recycled aggregate attached to the mortar after research. The reason for these poorer properties of recycled aggregates is the more complex interfacial structure of recycled aggregates [15]. Ordinary concrete is a three-phase nonuniform composite material consisting of natural coarse aggregate, fresh mortar, and the interface ITZ-1 located between natural coarse aggregate and fresh mortar [16]. Recycled aggregate concrete is a six-phase non-uniform composite material, including interface ITZ-1 located between recycled coarse aggregate and new mortar, interface ITZ-2 between recycled coarse aggregate and old mortar, and interface ITZ-3 located between new mortar and old mortar, which has been characterized by scanning electron microscopy [17], X-ray microtomography [18], and optical microscope thin sections [19]. The internal interfaces of recycled aggregate concrete were analyzed, and the results showed that the interfacial transition zone exhibited large porosity [17],

especially the ITZ-3 interface between the old and new mortar not only exhibited large porosity but also the width was about 15 μm larger than that of ITZ-1 and ITZ-2 [20]. The loose mortar on the surface layer of recycled aggregates results in lower concrete durability than ordinary concrete, which limits its application. Therefore, it is necessary to enhance the recycled aggregate to improve its concrete durability and better apply it to practical projects.

Currently, some scholars believe that the carbonation mechanism of recycled aggregate concrete is more complicated compared to ordinary concrete [21] due to the more complex interfacial structure [15]. The carbonation reaction products can fill the pores and cracks of recycled aggregate and improve the interfacial transition zone, thus enhancing its performance and concrete durability. In recent years, many scholars have been studying the improvement of carbon dioxide carbonation on recycled aggregates and their concrete properties. Studies have demonstrated that the carbonation reaction can considerably reduce the porosity of recycled aggregates. Yuan Chengfang et al. [22] discovered that the total porosity of cement paste decreased by approximately 19% to 40%. Kuang Tong [23] and Tang Wei [24] also observed that the pore size structure improved and porosity diminished after carbonation and that the water/cement ratio and hydration time of virgin concrete influenced this. Carbonation results in the conversion of calcium hydroxide to calcium carbonate, which causes a change in the crystal structure. This transformation reduces the number of connected pores and enhances the pore structure. Furthermore, the water absorption of recycled aggregates can be effectively reduced by up to 20–30% through carbonation, which is achieved by filling pores and crevices with substances such as calcium carbonate. Kou et al. [25] discovered that the water absorption of recycled fine aggregate was decreased by 56.89% following 72 h of treatment with carbon dioxide. The water absorption of cement mortar was significantly reduced following treatment with calcium hydroxide immersion, as demonstrated by the study conducted by Zhan et al. [26]. After pretreatment with industrial wastewater, Fang et al. [27] carbonized recycled coarse aggregate, substantially reducing the water absorption of recycled coarse aggregate. Simultaneously, the quality and microhardness of recycled aggregates were improved, as evidenced by a reduction of up to 25% in their pulverizing value following carbonization. In conclusion, carbonization technology offers a viable approach to enhance the performance of recycled aggregates.

Shi et al. [28] found that the microhardness of the interfacial transition zone increased by 40.3% after carbonization. Li et al. [29] indicated that after 7, 14, and 28 days of carbonization, the average cracks in the interfacial transition zone of recycled coarse aggregate with 10–20 mm particle size were reduced to the uncarbonized value of 39.7%, 20.5%, and 14.2%, respectively. Zhan et al. [27] reported that carbonation made the surface of cement mortar harder, and the microhardness of the pretreated samples was higher at 0–2 mm depth and stable after 4 mm depth. Carbonation reduces water absorption and porosity by changing the pore structure, which increases the microhardness and reduces the crushing value.

Wang et al. [30] treated recycled coarse aggregate with a 20% concentration of carbon dioxide, which increased the apparent density by 3.34%. Li et al. [31] found that the apparent density increased from 2583 kg/m^3 to 2604 kg/m^3 after carbonization, but the increase was no further increased with the passage of time, as the pore space was filled with calcium carbonate and the carbonization reaction was blocked. Zhan et al. [27] reported that after the carbonization treatment of recycled aggregate, the carbonization effect was not obvious from the depth of 4 mm to the center. Therefore, accelerated carbonization treatment can increase the apparent density of recycled aggregate to some extent, but the increase is not obvious. Ying Jingwei et al. [32] found that the overall compressive strength of concrete in-

creased by decreasing the replacement rate of recycled aggregate, but it was still lower than that of normal concrete. Luo et al. [33] pointed out that the relative compressive strength of recycled coarse aggregate increased by 3% when 30% of it was replaced by carbonation and increased by 33% when 100% was replaced by recycled aggregate. Ding Jinwei et al. [34] found that the compressive strength decreased by 12.6% with 40% replacement of recycled fine aggregate and only 4.7% after carbonation, attributed to the reduction of porosity by carbonation. The 7- and 28-day compressive strengths of carbonated recycled aggregate concrete were intermediate between those of normal and recycled concrete, indicating that carbonation compensates for the loss of strength. Ying Jingwei et al. [32] also found that the loss of 28-day compressive strength of concrete was reduced by increasing the replacement rate of carbonation with recycled coarse aggregate, and the strength increased by 7.6% at 100% replacement. Medina et al. [35] noted that carbonation increased the tensile strength of concrete by increasing the apparent density of recycled aggregate. Tam et al. [36] found that the tensile strength of carbonated recycled coarse aggregate with 30% replacement was higher than that of normal concrete. Zhang Shaokun et al. found that the tensile strength of recycled aggregate concrete prepared from recycled aggregate could be increased by up to 28.8% after carbonization using different concentrations of calcium hydroxide solution immersion. After carbonization treatment, the water absorption of recycled aggregate was reduced, the apparent density was increased, the effective water/cement ratio of recycled aggregate concrete was reduced, and the concrete was denser, thus significantly increasing the tensile strength of recycled concrete [37]. Xuan et al. [38] found that the flexural strength of recycled aggregate concrete was comparable to that of ordinary concrete when 60% of recycled coarse aggregate was replaced by carbonation, and the flexural strength increased by 28.7% when 100% was replaced. Tam et al. [36] indicated that the flexural strength of recycled coarse aggregate was higher than that of ordinary concrete when 30% of recycled aggregate was replaced by carbonation. These phenomena indicate that the carbonation technique significantly improves the flexural strength of recycled aggregate concrete due to the carbonation products filling the pores and improving the transition zone between old and new interfaces.

This paper examines the direct carbonization treatment of recycled aggregates in order to thoroughly evaluate its impact on the performance enhancement of recycled aggregates. Additionally, the pre-soaking treatment is implemented to investigate the performance enhancement of recycled aggregates following carbonization. The optimal range of calcium hydroxide concentration is subsequently determined. Furthermore, the efficacy of the ultrasonic cavitation treatment on the post-carbonation properties of the recycled aggregates was evaluated, as well as the optimal power range for ultrasonic cavitation. Lastly, the exhaustive investigation of the synergistic improvement effect of the combined treatment of ultrasonic cavitation and pre-soaking on the carbonization degree of recycled aggregate was conducted with the objective of establishing a solid foundation for future enhancements to the carbonization degree.

2. Materials and Methods

2.1. Raw Materials

The test utilizes PO42.5 ordinary silicate cement manufactured and supplied by Shanshui Group. The pertinent indexes satisfy the specifications of "Ordinary Silicate Cement" (GB175-2007) [39], and the primary chemical composition is indicated in Table 1. The particle size of recycled coarse aggregate is 5–25 mm, and it is obtained from conventional concrete specimens through standardized maintenance and crushing screening. In accordance with the GB/T14684-2001 [40] standard, fine aggregate is composed of natural river sand. The fine aggregate is natural river sand that complies with the GB/T14684-2001 [40]

standard. The test was conducted using conventional tap water from the comprehensive civil engineering laboratory building, which had a 1 g/cm^3 density. The carbon dioxide gas was a high-purity compressed gas with a purity of over 99%, supplied by Xinyi Gas Company. The internal pressure was maintained at (14.5 ± 0.5) MPa, and the carbon dioxide cylinder had a capacity of 40 L. The raw material for the precise configuration of a succession of calcium hydroxide solutions of varying concentrations was high-purity calcium hydroxide powder. The high-purity calcium hydroxide powder was weighed and dissolved in a suitable solvent to create a transparent solution. The concentrations were set at 0.01 mol/L, 0.04 mol/L, 0.07 mol/L, and 0.1 mol/L.

Table 1. Portland cement composition (%).

Chemical Composition	Cao	Al_2O_3	TiO_2	Fe_2O_3	SiO_2	SO_3	K_2O	Na_2O
content	57.28	6.23	1.07	6.79	21.74	3.48	0.62	0.56

2.2. Specimen Forming and Maintenance

2.2.1. Pretreatment of Recycled Aggregate

After a rigorous curing process meeting the national standard, ordinary concrete specimen blocks are removed from the constant temperature and humidity chamber at the ages of 14d, 28d, and 90d. The recycled coarse aggregate is separated from 5 mm to 25 mm by screening after a jaw crusher pulverizes it.

2.2.2. Regenerated Aggregate Carbonization Treatment

The well-sealed carbonation chamber, which has precise temperature control, was used to sequentially position the screened recycled coarse aggregates to replicate the concrete carbonation environment. The carbonation test was conducted at a concentration of carbon dioxide of (20 ± 2)%, humidity of (65 ± 5)%, and a temperature of (20 ± 2) °C.

2.2.3. Regenerated Aggregate Concrete Specimen Forming and Curing

Ensure that the recycled aggregate, cement, sand, and water are weighed accurately per the pre-designed mix ratio (0.4) to ensure that the materials comply with the standard and protect the concrete's consistent performance. The recycled aggregate was initially poured into the mixing container and premixed without water for 90 s to prevent subsequent material accumulation. Subsequently, gradually incorporate cement and grit into the mixture and continue dry mixing for 90 s to guarantee that all three are uniformly combined. Next, mix the mixture while adding water to prevent localized over-wetting. After adding water, moisten the mixture for 2 min. Wet mixing ensures the cement is thoroughly hydrated, a stable cementitious system is formed, and all materials are evenly dispersed without lumps or segregation. This process ensures the overall performance and accuracy of the concrete.

The mixed concrete was promptly poured into the molds, which were 100 mm × 100 mm × 100 mm, 100 mm × 100 mm × 400 mm, and 150 mm × 150 mm × 150 mm. The surface was subsequently smoothed and inscribed with the date and number. After the initial setting (approximately 24 h), the concrete was demolded and deposited in a standard curing room to cure until the specified ages of 3d, 7d, and 28d occurred. In order to evaluate the mechanical properties of the recycled aggregate concrete, specimens were extracted for compressive, flexural, and split tensile strength experiments. The concrete pouring, vibration, polishing, marking, and curing operations are standardized throughout the entire process to guarantee the accuracy of the test results.

2.3. Experimental Scheme

2.3.1. Detection of Temperature, Humidity, and Carbon Dioxide Content During the Carbonization Process

A standardized carbonization chamber, equipped with sophisticated multi-parameter sensors, is employed to guarantee the accuracy and consistency of the carbonization process of recycled coarse aggregate. Scientific principles and engineering standards are strictly adhered to during the test to ensure the precise regulation of environmental parameters. These parameters include temperature (20 ± 2) °C to maintain thermodynamic equilibrium, humidity (65 ± 5)% to prevent dryness or humidity-induced blockage of the carbonization process or side reactions, and carbon dioxide concentration (20 ± 2)%, which is maintained by high-precision technology to ensure a constant and suitable carbonization atmosphere. The recycled coarse aggregate is carbonized efficiently in a precise and consistent environment, enhancing the treatment results. All settings allow for very minor deviations.

2.3.2. Physical Properties Test of Regenerated Aggregate Before and After Carbonization

The apparent density, water absorption, and crushing index were used to characterize the physical properties of regenerated aggregate after carbon dioxide strengthening, pretreatment, and carbonization strengthening. According to the relevant provisions of JGJ52-2006 [41] "Standard for Quality and Inspection Methods of sand and stone for Ordinary concrete", the specific methods of each index test are as follows:

Determination of water absorption: weigh 500 g sample into the dish, add water until the water surface is about 20 mm higher than the surface of the sample, soak for 24 h, remove from the water, wipe the water on the surface of the particles with a wet towel, that is, make a saturated-surface dry sample, and immediately weigh out its mass, recorded as G_1 accurate to 1 g. The saturated surface dry sample was dried in a drying oven at (105 ± 5) °C to a constant amount. After cooling to room temperature, its mass was measured to 1 g accurately and recorded as G_2.

Water absorption is calculated according to the following formula; the exact value is 0.01%.

$$W = (G_1 - G_2)/G_2 \quad (1)$$

where W corresponds to water absorption rate (%); G_1 corresponds to the mass of the saturated face dry sample, in grams (g); G_2 corresponds to the mass of the dried sample, expressed in grams (g).

Apparent density measurement: According to the steps in the JGJ52-2006 standard, the apparent density of the RCA aggregate with a particle size between 5 mm and 25 mm is first selected, and the selected RCA aggregate is put into water until the RCA reaches saturation, and then the RCA is taken out and dried with a dry towel until the saturated surface is dry. The RCA is then placed into the jar and water is poured into the jar. When the water overflows the jar, the jar is stopped, and the air bubbles are removed by tapping the wall with your hand. Finally, cover the bottle with ground glass sheet, and use a dry towel to dry the surface of the bottle and the water stains attached to the glass sheet, and weigh the glass sheet, the bottle, the water, and the quality G_1 of RCA. After weighing, pour out the water in the glass bottle, take out the RCA, dry the RCA in the oven to constant weight, and weigh the RCA weight G_2 at this time. Pour water into the wide-mouth bottle until it overflows, cover the ground glass sheet, wipe the surface water stains, and weigh the wide-mouth bottle, water, and glass sheet quality G_3; Formula (2) was used for calculation

$$D = \left(\frac{G_2}{G_2 + G_3 - G_1} - \partial_t\right) \times 1000 \quad (2)$$

where D corresponds to the calculation result of the apparent density of RCA.

Determination of crushing index: Take the minimum sample mass after drying (9 kg), screen out particles greater than 20 mm and less than 10 mm, and remove needle and flake particles, divided into roughly equal three parts for use. When there are insufficient particles with a particle size between 10 and 20 mm in the sample, particles with a particle size greater than 20 mm are allowed to be broken into particles with a particle size between 10–20 mm for crushing index test.

Weigh the sample 3000 g, accurate to 1 g. The sample is divided into two layers into the pressure test mold round die (placed on the chassis). After each layer of sample is installed, put a 10 mm diameter round steel under the chassis, press the cylinder, and alternately hit the ground 25 times. After the two layers are overturned, smooth the surface of the sample in the mold and cover the indenter. When the round mold cannot hold 3000 g sample, it should be installed 10 mm away from the top of the round mold.

Put the round mold with the sample on the pressure testing machine, start the pressure testing machine, evenly load at the speed of 1 kN/s to 200 kN, stabilize the load for 5 s, and then unload. Remove the pressure head, pour out the sample, sift out the crushed fine particles with a 2.36 mm aperture screen, and weigh the sample mass remaining on the screen to an accuracy of 1 g.

The crushing index is calculated according to the following formula, accurate to 0.01%.

$$Q_e = (G_1 - G_2)/G_1 \times 100\% \quad (3)$$

where Q_e corresponds to crushing indicator, %; G_1 corresponds to the mass of the sample, expressed in grams (g); G_2 corresponds to the mass of the sample remaining after the crushing test, in grams (g).

Based on the above description, in order to further improve the carbonization effect through carbonization enhancement, three new methods are used to improve the performance of recycled aggregate after treatment and then carbonization, which provides the basis for further promotion of recycled aggregate use. Uncarbonated recycled aggregate, directly carbonated recycled aggregate (CRCA), calcium hydroxide presoaked recycled aggregate (L-RCA), ultrasonic cavitation treated recycled aggregate (W-RCA) and ultrasonic cavitation-calcium hydroxide presoaked recycled aggregate (W-L-RCA) were carbonized. The mechanical properties of carbonized recycled aggregate and recycled aggregate concrete were investigated.

3. Results

3.1. Study on Physical Properties of Carbonized Reinforced Recycled Aggregate

3.1.1. RCA Physical Performance

The wet apparent density is a critical parameter for evaluating recycled aggregate quality. It is determined by dividing its mass by its apparent volume. It is widely accepted that the wet apparent density indicates the degree of internal densification. In the experiment, we selected recycled aggregate samples of varying ages (14d, 28d, 90d) and particle sizes (5–25 mm) for measurement. We observed that the apparent density increased with age, from 2508 kg/m^3 to 2522 kg/m^3, indicating that the recycled aggregate became denser internally as it aged and that the porosity decreased. This is due to the ongoing internal hydration reaction, which fills the pores and fractures with hydration products like hydrated calcium silicate, reducing apparent volume.

Meanwhile, the efficacy of recycled aggregate is also significantly influenced by its water absorption, which is closely correlated with porosity. The water absorption of recycled aggregates is generally higher than that of natural aggregates due to the bulk

of surface mortar, large pores, and wide interface fractures. Table 2 illustrates particular measurements. The water absorption of recycled aggregates decreased with age, from 5.79% at 14 days to 5.59% at 90 days, as indicated by the measurements in the experiments. This also suggests that the water absorption of recycled aggregates is lower than that of natural aggregates. This also reflects the alteration in the internal porosity of the recycled aggregate. As the age of the aggregate increases, the pores and fractures are filled with more hydration reaction products, which reduces the amount of water remaining inside after the same soaking time.

Table 2. Physical properties of recycled aggregate.

Water/Cement Ratio	Age (Days)	Water Absorption (%)	Apparent Density (kg/m^3)	Crush Indicator (%)
0.4	14	5.79%	2508	17.60
	28	5.66%	2518	18.40
	90	5.59%	2522	18.60

The recycled aggregate's quality is determined by its pulverizing index; a lower index indicates superior quality. The crushing index of 5–25 mm recycled aggregate was measured at the ages of 14d, 28d, and 90d in the test context. The results showed that the crushing index increased from 17.6% to 18.6% as the aggregate age increased, indicating that the quality of the recycled aggregate deteriorated. The reason for this is that the hydration of cement becomes more complete as it ages, the impact force during crushing is significant, and the mortar is not dense, all of which contribute to the increase in the crushing index.

3.1.2. Physical Properties of CRCA

The properties of recycled aggregate are illustrated in Figure 1 before and after the carbonization treatment. The water absorption rate of recycled aggregate at various ages was reduced by 8.12% at 14d, 9.89% at 28d, and 9.30% at 90d after carbonization treatment, as illustrated in Figure 1a. This suggests that carbonization effectively reduced the water absorption capacity of recycled aggregate, with the 28d and 90d aggregates exhibiting a more substantial reduction.

Figure 1b illustrates that the apparent density of recycled aggregate was enhanced at all ages following carbonization, with increases of 2.51% at 14d, 2.82% at 28d, and 2.78% at 90d, respectively. These data suggest that carbonization treatment benefits the apparent density, although the overall increase is not immediately obvious.

The pulverizing indexes of recycled aggregates were all reduced after carbonization, as illustrated in Figure 1c. The decreases were 6.91% at 14d, 7.61% at 28d, and 9.68% at 90d, and the change trends were consistent with water absorption and apparent density.

The carbonation reaction alters the properties of recycled aggregates, which occurs when carbon dioxide reacts with the hydration products of cement to produce calcium carbonate. This compound fills cracks and voids and reduces porosity, internal moisture, and water absorption, thereby reducing water absorption. Additionally, the volume of the hardening products increases, improving compactness and apparent density and reducing the crushing index. The carbonation effect of recycled aggregate is lower at 14d than at 28d and 90d, which may be attributed to the prolonged age period. The carbonizable material increases, and the cement's hydration is complete. Nevertheless, the carbonation effect of 90d aggregate was slightly diminished, likely due to the rapid carbonation rate and the impediment of the reaction by the products. However, the carbonation effect of 90d aggregate is still superior to that of 14d.

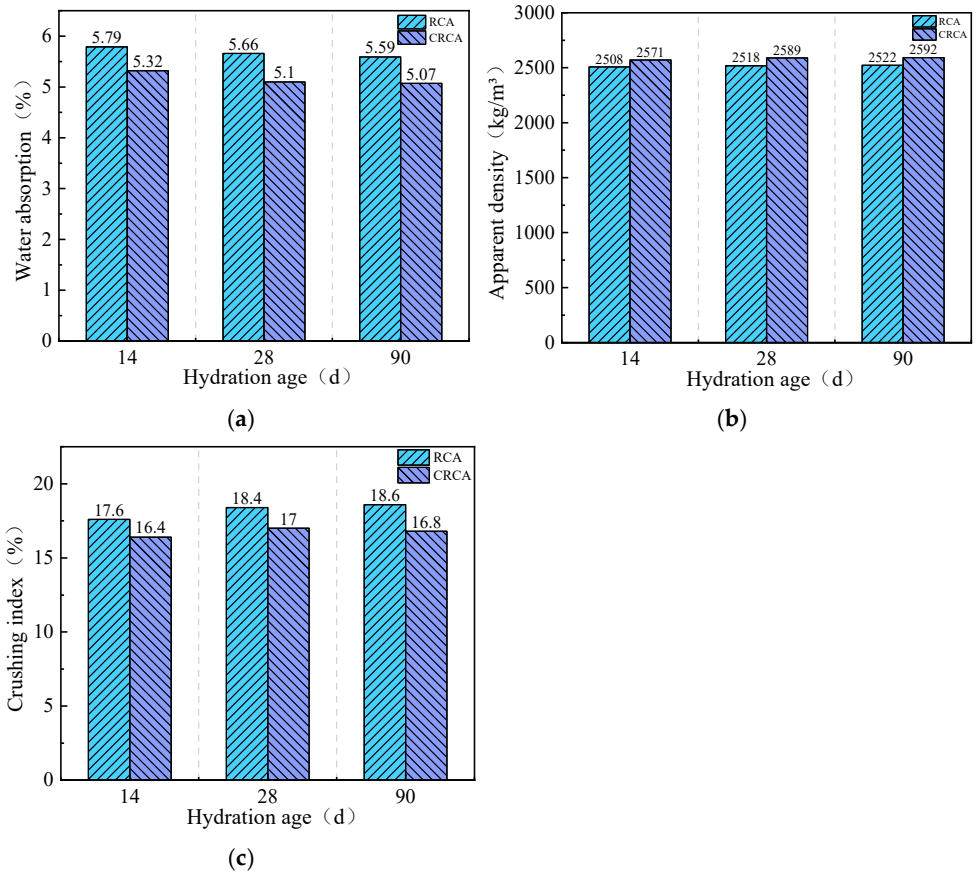


Figure 1. CRCA physical properties. (**a**) Water absorption; (**b**) apparent density; (**c**) crushing index.

3.1.3. Physical Properties of L-RCA After Carbonization

The water absorption of recycled aggregate recarbonized after calcium hydroxide pretreatment was further reduced, as illustrated in Figure 2. The water absorption of the 14d recycled aggregate was decreased by 1.32–7.33%, which is equivalent to a reduction of up to 13.51% when compared to the uncarbonized recycled aggregate. The 28d recycled aggregate was reduced by 1.37–3.73%, equivalent to a reduction of up to 13.25% compared to the uncarbonized recycled aggregate. The 90d recycled aggregate was decreased by 0–3.16%, comparable to a reduction of up to 12.16% compared to the uncarbonized recycled aggregate. Most notably, the water absorption of 14d recycled aggregate was diminished, surpassing that of 28d and 90d recycled aggregate.

The apparent density of recycled aggregates that were recarbonized after calcium hydroxide pretreatment increased, as illustrated in Figure 3. The apparent densities of recycled aggregate were increased by up to 1.24% (relative to direct carbonization) and 3.79% (relative to uncarbonized) in the 14d, 1.04% and 3.89% in the 28d, and 0.96% and 3.77% in the 90d. The apparent density of recycled aggregate was elevated at all ages, and the 14d recycled aggregate elevation was marginally superior to the 28d and 90d, similar to the water absorption results.

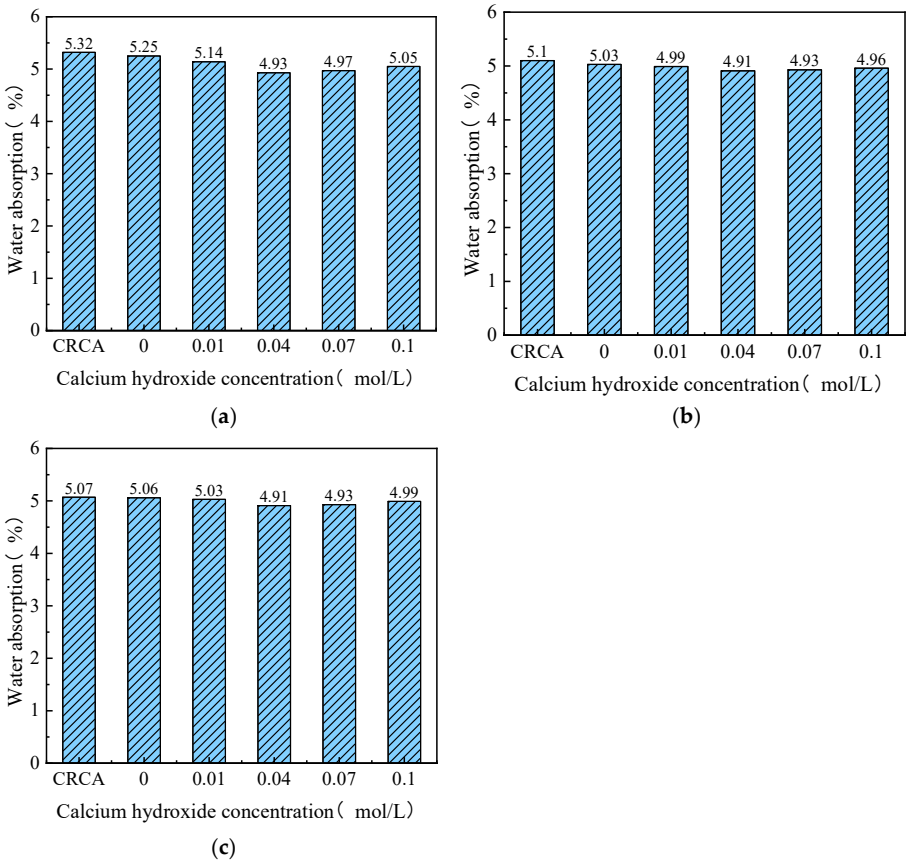


Figure 2. Water absorption of L-RCA. (**a**) 14 days age; (**b**) 28 days age; (**c**) 90 days age.

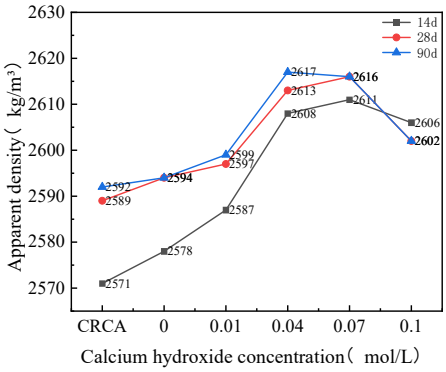


Figure 3. L-RCA apparent density.

The pulverizing index of the recycled aggregates that were recarbonized after calcium hydroxide pretreatment decreased, as illustrated in Figure 4. The crushing index of the recycled aggregates decreased by up to 9.69% (relative to direct carbonization) and 15.79% (relative to uncarbonization) at 14d, 7.52% and 14.67% at 28d, and 6.71% and 15.64% at 90d. In a manner similar to the results for water absorption and apparent density, the crushing index of recycled aggregates decreased at all ages, with a greater degree of reduction observed in 14d recycled aggregates.

The most effective enhancement effect is achieved by treating recycled aggregate with calcium hydroxide after carbonation at a concentration of 0.04 mol/L to 0.07 mol/L. This is due to the fact that the calcium ion increases the carbonizable material, which in turn accelerates the generation of calcium carbonate to fill the pores. The reaction is impeded by calcium carbonate when the concentration is excessive, resulting in a decrease in the rate of carbonization. Consequently, it is advised to employ this concentration range for treatment.

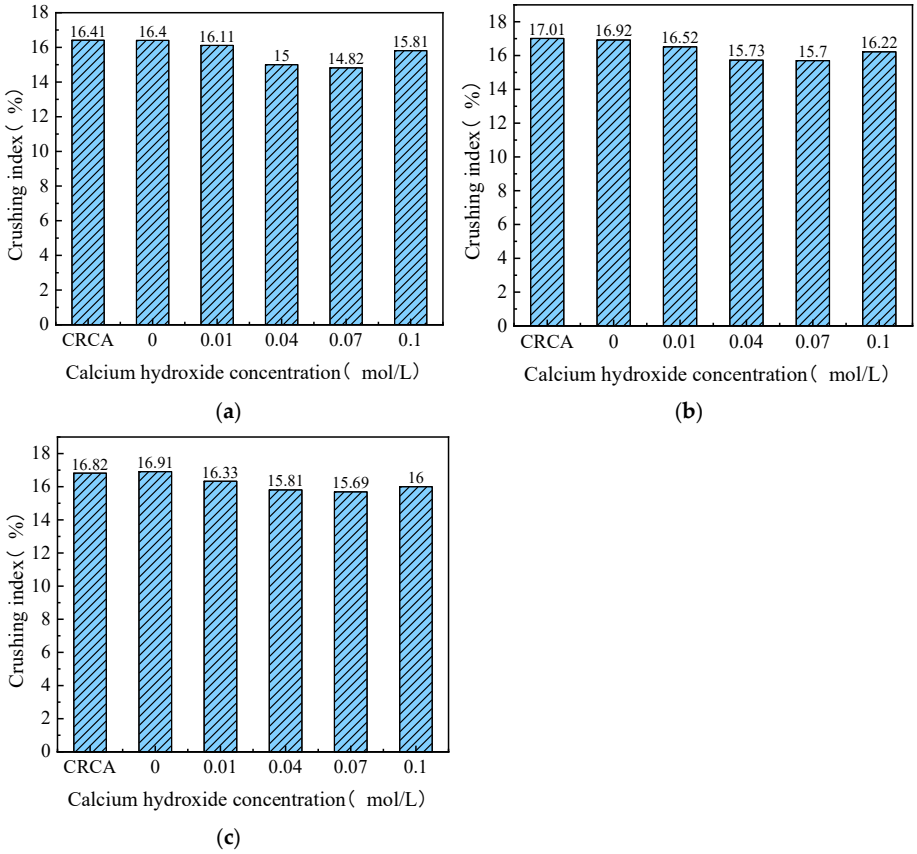


Figure 4. L-RCA crushing indicator. (**a**) Recycled aggregates 14 days of age; (**b**) 28 days of age; (**c**) 90 days of age.

The calcium hydroxide treatment of recycled aggregates of varying ages resulted in apparent differences in enhancing various performance parameters, including water absorption, apparent density, and crushing indexes. The recycled aggregates exhibited the most substantial improvement at the 14-day age, while their efficacy was not immediately obvious at the 28-day and 90-day ages. This is associated with the extent of mortar hydration on the recycled aggregate surface layer. The carbonate material is adequate, and the role of additional calcium ions is limited. The hydration of concrete at 28 days of age is nearly complete. The hydration of recycled aggregate is active at the 14-day age, and the carbonate material is reduced. The calcium hydroxide treatment can rapidly penetrate and participate in hydration, promoting mortar densification and significantly improving carbonation and performance indicators. Consequently, it is advisable to employ calcium hydroxide treatment for recycled aggregate that is brief in age following carbonization.

3.1.4. Physical Properties of W-RCA After Carbonization

The water absorption of recycled aggregate carbonized by ultrasonic cavitation decreased to 14d, 28d, and 90d, as illustrated in Figure 5. The absorption of recycled aggregate water decreased by 9.84% to 10.71% (relative to uncarbonized) and 2.82% (relative to direct carbonization) in 14.d, 11.13% to 13.78% and 4.31% in 28d, and 9.48% to 12.34% and 3.35% in 90d. A decreasing overall trend was observed, with the degree of decrease for 28d and 90d being greater than that of 14d. The reduction of water absorption after carbonization was most pronounced at 40 W ultrasonic cavitation power, and the effect of ultrasonic cavitation treatment became more pronounced as the age of the material increased.

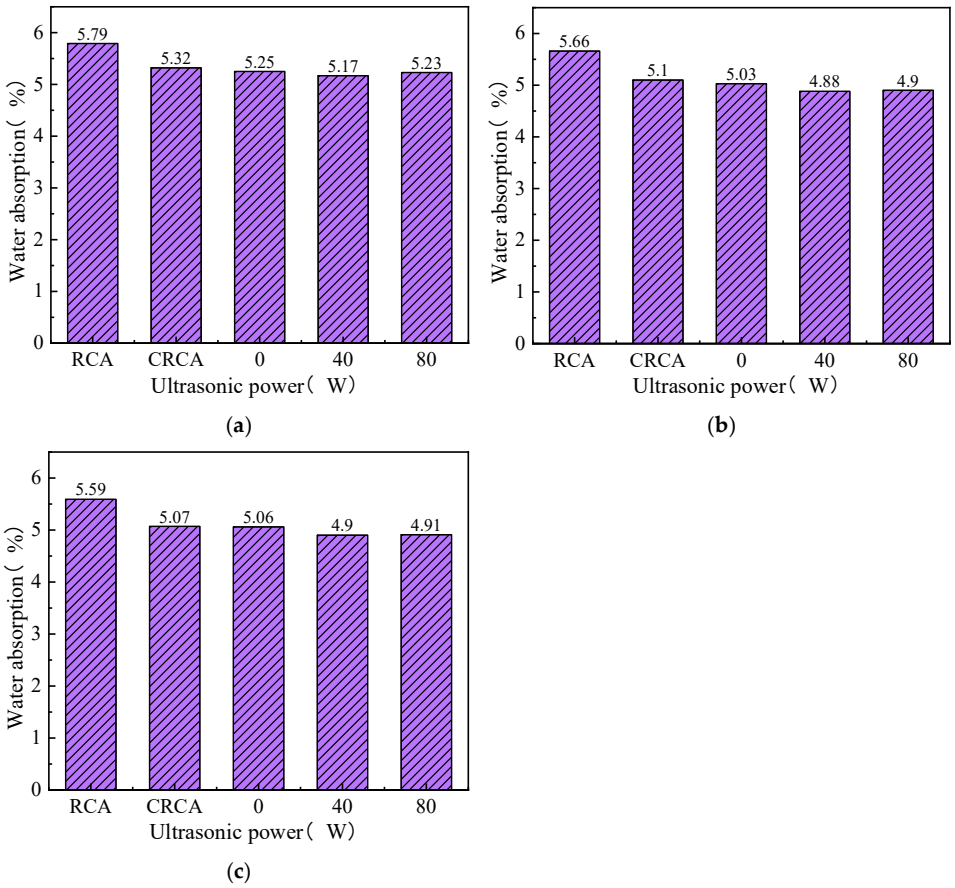


Figure 5. Water absorption of W-RCA. (**a**) Recycled aggregates at 14 days of age; (**b**) 28 days of age; (**c**) 90 days of age.

The apparent density of recycled aggregates at various ages can be substantially improved by ultrasonic cavitation treatment, as illustrated in Figure 6. The untreated group and the direct carbonization group were outperformed by the 14d age samples, which were treated with a maximal enhancement of 3.19%. The maximum improvement was 3.69%, and the range of improvement was extended to 0.19%~0.85% at the age of 28d. The treatment continued producing a 0.08–0.77% enhancement, and the maximum enhancement marginally decreased to 3.5% despite the internal structure stabilizing at 90 days of age. The treatment effect was more pronounced with age, particularly at 40 W ultrasonic power. In summary, the apparent density of recycled aggregates was substantially enhanced by the combination of ultrasonic cavitation and carbonization treatment. In order to optimize the carbonation effect, 40~60 W ultrasonic power cavitation pretreatment is more appropriate for long-age recycled aggregates. In contrast, short-age aggregates have a limited impact due to insufficient cement hydration.

According to Figure 7, the pulverizing index of recycled aggregate demonstrated a decreasing trend following ultrasonic cavitation treatment compared to the direct carbonization treatment. This suggests that the carbonization treatment can potentially enhance recycled aggregate quality. Recycled aggregate's crushing index was reduced by up to 3.72%, 11.82%, and 12.01% after ultrasonic cavitation treatment in comparison to the direct carbonization treatment and by up to 10.27%, 18.48%, and 20.43% in comparison to the uncarbonized treatment at the ages of 14d, 28d, and 90d, respectively. More specifically, the aggregate was substantially enhanced at 14 days of age by 40 W ultrasonic power, with a greater improvement at 28 days and 90 days of age. This is due to the bubble rupture effect generated by ultrasonic cavitation, which can remove impurities from the aggregate surface,

increase its contact area with carbon dioxide, accelerate the carbonation reaction, increase carbonate generation, and improve aggregate structural densification. Consequently, the water absorption reduction, decrease in crushing index, and increase in apparent density are the results.

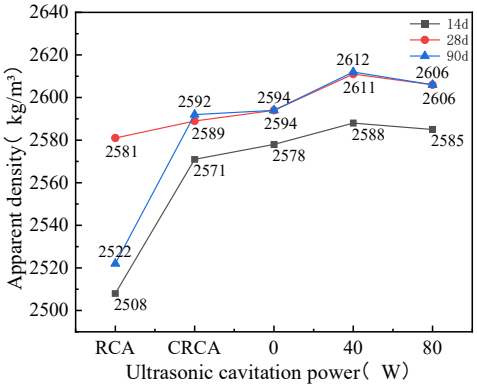


Figure 6. W-RCA apparent density.

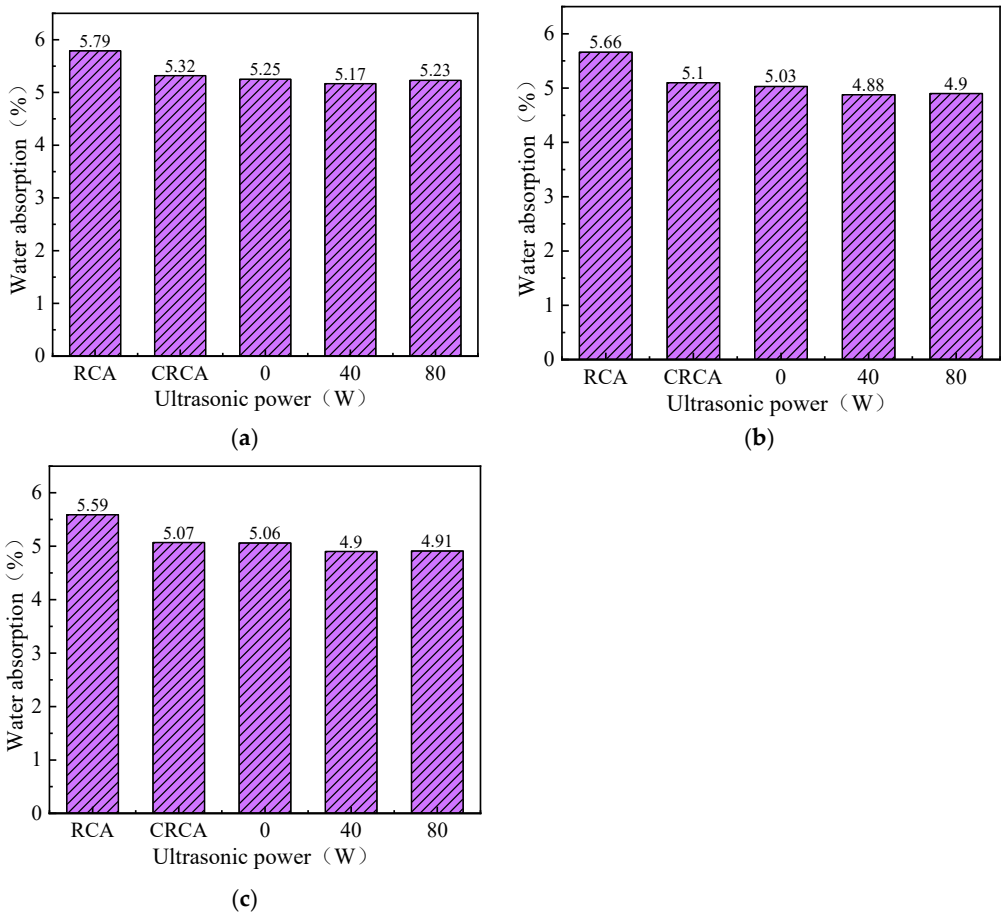


Figure 7. W-RCA crushing indicator. (**a**) Recycled aggregates at 14 days of age; (**b**) 28 days of age; (**c**) 90 days of age.

3.1.5. Physical Properties of W-L-RCA After Carbonization

The impact of ultrasonic cavitation with calcium hydroxide pre-soaking treatment on water absorption after carbonization of recycled aggregates is illustrated in Figure 8. Following carbonization through ultrasonic cavitation and calcium hydroxide pre-soaking, water absorption was reduced by up to 3.22%, 4.06%, and 5.30% in recycled aggregates of 14d, 28d, and 90d ages, respectively. Furthermore, the ultrasonic cavitation power and calcium

hydroxide concentration significantly influence the pretreatment effect. The synergistic effect, surface modification, and internal microstructure reorganization of aggregate can be enhanced by increasing the power of ultrasonic cavitation at a suitable concentration. This can also facilitate the better penetration of calcium hydroxide solution, thereby reducing the water absorption rate.

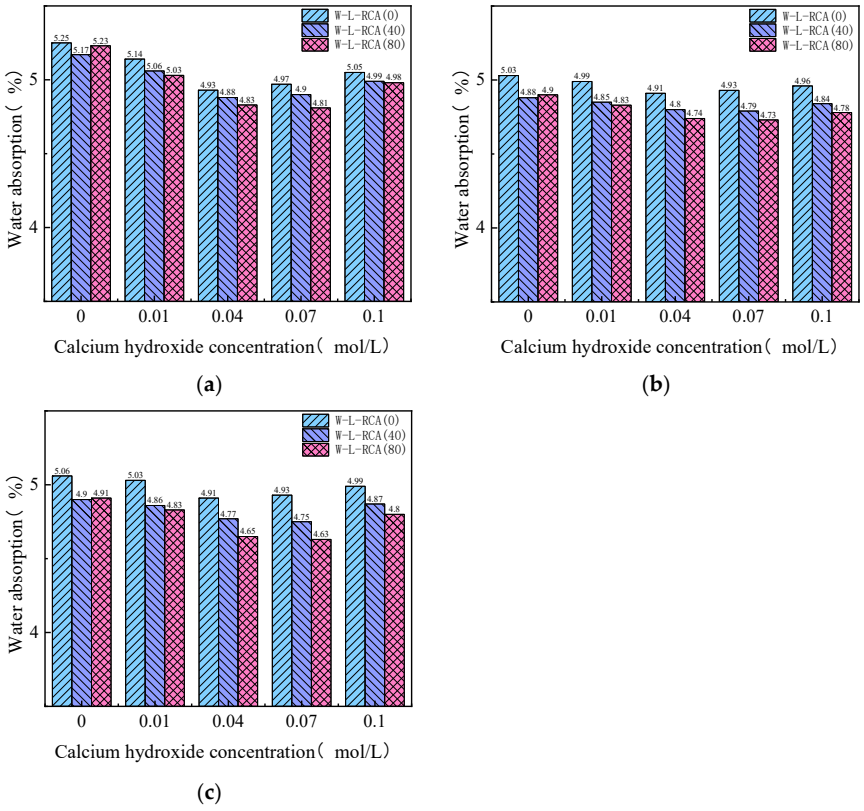


Figure 8. Water absorption of W-L-RCA. (**a**) Recycled at 14 days of age; (**b**) 28 days of age; (**c**) 90 days of age.

The apparent density of the recycled aggregates carbonized by ultrasonic cavitation with calcium hydroxide pre-soaking pretreatment was enhanced, as illustrated in Figure 9, in accordance with the trend of increased water absorption. The apparent density of the recycled aggregates was improved by approximately 0.5%, 0.57%, and 0.50% at the ages of 14d, 28d, and 90d, respectively. Although the improvement is not substantial, it still suggests that the combined pretreatment technique has the potential to enhance the physical properties of recycled aggregates to a certain extent, thereby demonstrating the possibility of optimizing the overall performance.

The compression index was significantly reduced after carbonation as a result of pre-soaking 14d, 28d, and 90d recycled aggregates with calcium hydroxide following ultrasonic cavitation, as illustrated in Figure 10. The crushing index of 14d, 28d, and 90d recycled aggregates was reduced by up to 13.18%, 13.78%, and 9.14%, respectively, by the combined treatment, which was superior to ultrasonic cavitation or pre-soaking alone, when compared to the treatment alone. The water absorption and apparent density enhancement results were consistent with the optimal treatment conditions of a calcium hydroxide concentration of 0.04–0.07 mol/L and an ultrasonic cavitation power of 40 W.

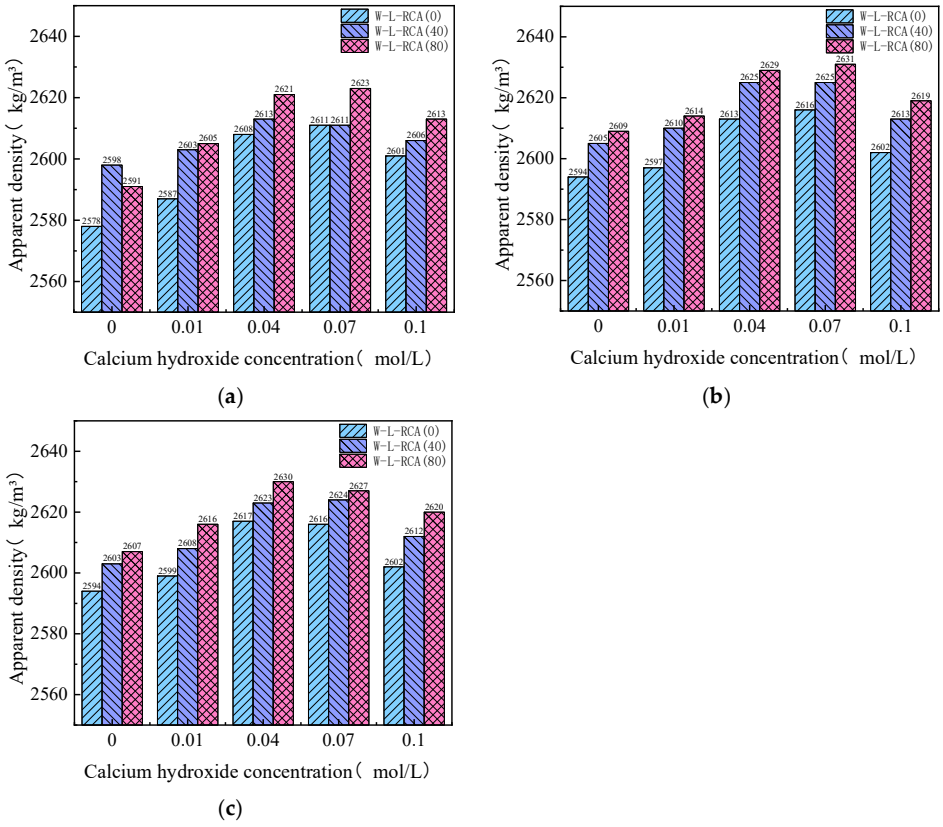


Figure 9. W-L-RCA apparent density. (**a**) Recycled aggregates at 14 days of age; (**b**) 28 days of age; (**c**) 90 days of age.

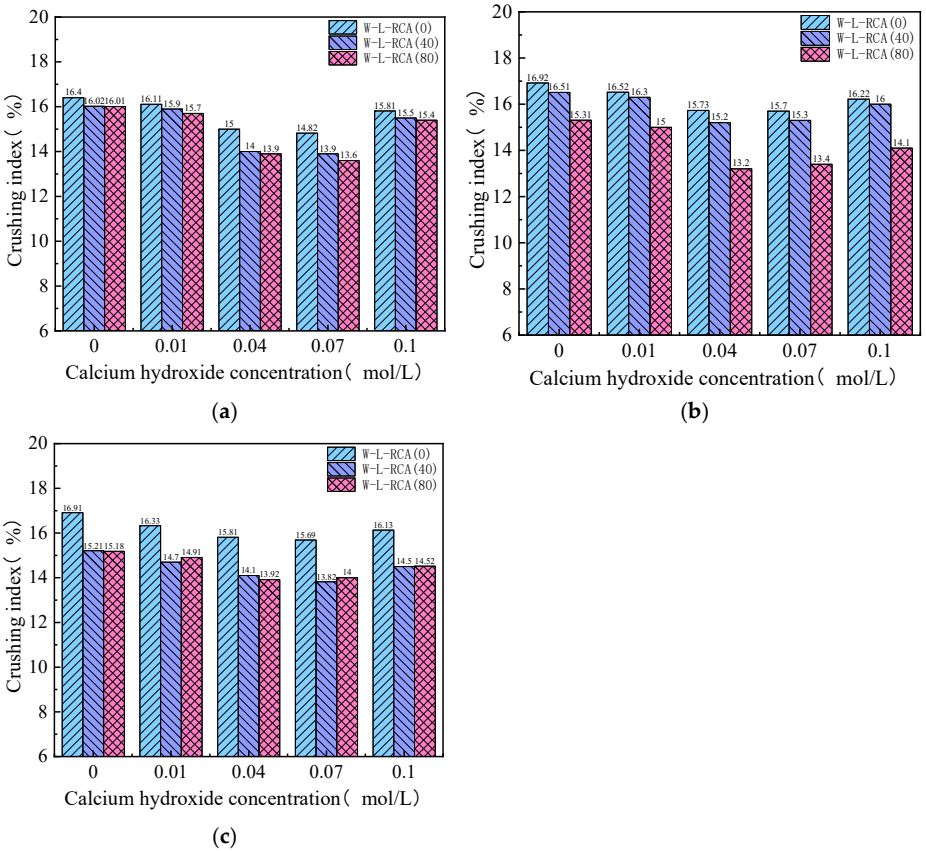


Figure 10. W-L-RCA crushing indicator. (**a**) Recycled aggregates at 14 days of age; (**b**) 28 days of age; (**c**) 90 days of age.

The physical properties of recycled aggregates are considerably enhanced by ultrasonic cavitation-pre-soaking pretreatment, which is superior to direct carbonization or single pretreatment. This includes a lower water absorption, a higher apparent density, and a lower crushing index. By forming and collapsing cavitation bubbles, ultrasonic cavitation optimizes the pore distribution and influences the aggregate pore structure. The chemical activity on the aggregate surface is improved by calcium hydroxide pre-soaking, which also facilitates the deposition of calcium carbonate during carbonization, resulting in a denser structure. This technique substantially impacts recycled aggregates that are 14d, 28d, and 90d old. The optimal treatment conditions were a calcium hydroxide concentration of 0.04–0.07 mol/L and an ultrasonic cavitation power of 40–80 W. However, the power enhancement was excessive, resulting in a reduction in the treatment efficacy.

3.2. Micromechanical Study of Carbonized Recycled Aggregates

3.2.1. XRD Analysis of Recycled Aggregate Attached Mortar

To analyze the XRD diffraction patterns of the slurry attached to the surface of the recycled aggregate following carbonization treatment of RCA, CRCA, L-RCA, W-RCA, and W-L-RCA, tests were conducted.

The XRD diffraction results of untreated and directly carbonized recycled aggregates are illustrated in Figure 11. The findings indicate that the calcite characteristic peaks are significantly reduced in the carbon dioxide-treated recycled aggregate, whereas the intensity of the calcium hydroxide characteristic peaks is significantly reduced in the direct carbonization-treated recycled aggregate, and the calcium carbonate characteristic peaks are significantly enhanced. This implies that the carbonization treatment converted calcite and calcium hydroxide to calcium carbonate. The experiments were adequate to demonstrate this despite the absence of quantitative calculations for the specific values of reactants and products. Additionally, the recycled aggregates from the two treatments contain extremely low levels of calcite, which suggests that calcium carbonate is primarily converted from calcium hydroxide.

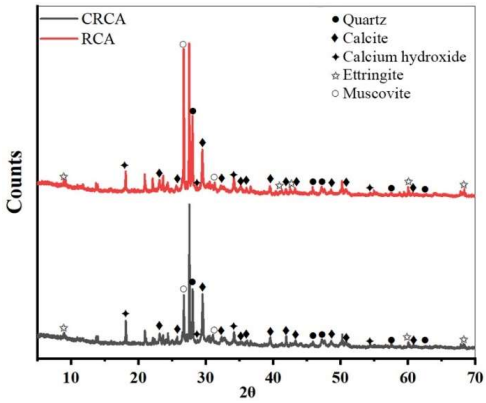


Figure 11. XRD pattern after CRCA treatment.

Figure 12 illustrates the XRD analysis results of W-RCA and L-RCA following the carbonization treatment. The regenerated aggregate pretreated with calcium hydroxide and carbonized exhibits a greater increase in the intensity of the calcium carbonate peak when compared to the regenerated aggregate treated with direct carbonization (Figures 11 and 12). This suggests that the pre-treated recycled aggregate is carbonized to a greater extent as a result of the pre-treatment, which enables a greater amount of calcium hydroxide to enter the interior of the aggregate and react with carbon dioxide to produce a greater amount of calcium carbonate. In contrast, the characteristic peak of calcium carbonate increased marginally, but not significantly, when the recycled aggregate was

carbonized after ultrasonic cavitation, and the recycled aggregate was carbonized directly. Consequently, the degree of carbonization can be marginally enhanced by the treatment of carbonization following ultrasonic cavitation; however, the effect is not substantial. The performance enhancement is not immediately apparent due to the fact that ultrasonic cavitation enhances the pore structure and expands the contact area of carbon dioxide. However, the carbonizable material in the recycled aggregate is restricted.

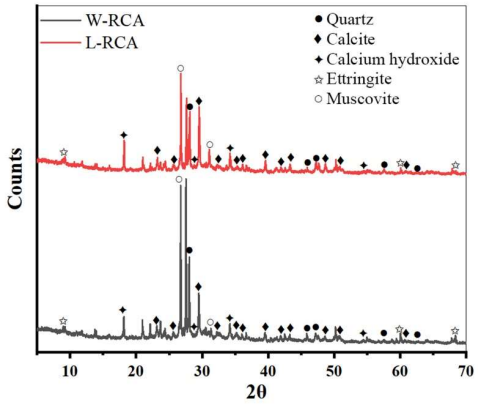


Figure 12. XRD pattern of L-RCA after carbonization treatment.

The XRD diffraction analysis pattern of carbonized recycled aggregate after ultrasonic cavitation-pre-soaking treatment is illustrated in Figure 13. The figure shows that the characteristic peaks of calcium carbonate are considerably increased, suggesting that the regenerated aggregate can generate more calcium carbonate and that the degree of carbonization is further enhanced resulting from this treatment. This may be attributed to the fact that ultrasonic cavitation enhances the pore structure and increases the specific surface area. Subsequently, the pores are subjected to pre-soaking, which results in the attachment of a greater amount of calcium hydroxide and the production of a greater amount of calcium carbonate during carbonization. Consequently, the recycled aggregate's quality was further enhanced, and the characteristic calcium carbonate peak was accentuated.

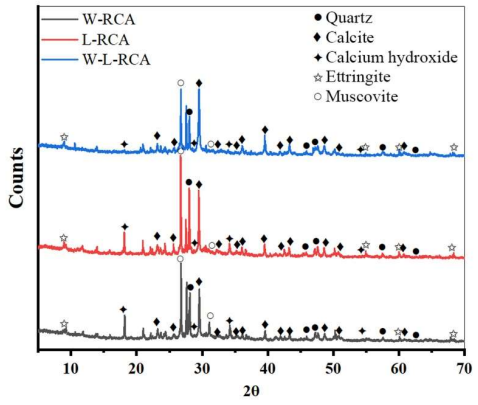


Figure 13. XRD pattern of W-L-RCA after carbonization treatment.

3.2.2. Infrared Spectral Analysis of Recycled Aggregates

The primary characteristics of molecular vibration are determined by the vibrational modes of the atoms in a substance group. Infrared spectroscopy primarily reveals the changes in the vibrational energy levels of the group, which can be used to analyze and deduce the type of substance. The carbonization of calcium hydroxide in cement material results in the formation of calcium carbonate crystals. As shown in Figure 14, The anti-symmetric telescopic vibration peak of the Si-O-Si bond in quartz is observed at 1100 cm^{-1},

while the characteristic peaks on the infrared spectrum of calcite generated by carbonation are located near 1424 cm^{-1}, 874 cm^{-1}, and 713 cm^{-1}. In the figure, the antisymmetric stretching vibration and out-of-plane bending vibration peaks of calcite are represented by the absorption bands at 1433 cm^{-1} and 877 cm^{-1}, respectively. The antisymmetric stretching vibration of the Si-O-Si bond is represented by the absorption band at 1084 cm^{-1}. The O-H bond stretching vibration in calcium hydroxide is represented by the 3435 cm^{-1} absorption peak.

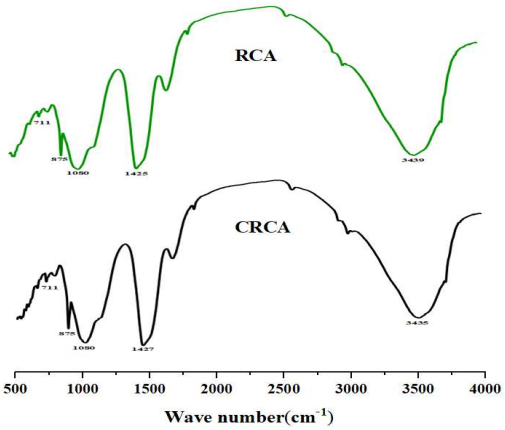


Figure 14. Infrared spectra after CRCA treatment.

The IR spectra of RCA (recycled aggregate) and CRCA (CO_2-treated recycled aggregate) were compared, as illustrated in Figure 14. We discovered that the absorption peaks of CO_2-treated samples are accentuated at 1433 cm^{-1} and 1084 cm^{-1}, and they are attenuated at 3435 cm^{-1}. The positive triangular structure vibration of carbonate is observed in the interval of 1410 cm^{-1}~1510 cm^{-1} of the infrared spectrum during carbonation, as the C=O bond of carbon dioxide is converted to C-O bond vibration. This reaction between carbon dioxide and calcium hydroxide in the recycled aggregate results in the formation of calcite. The increase in peak area at 1080 cm^{-1} of the CO_2-treated samples still suggests silica production, despite the fact that the Si-O-Si bonds in quartz sand interfere when analyzing the Si-O bonds in recycled aggregate.

In Figure 15, the IR spectra of L-RCA (pre-soaked and subsequently carbonized recycled aggregate) are analyzed. The absorption peak area at 1433 cm^{-1} for the pre-soaked treated recycled aggregate increases further, while the absorption peak near 1080 cm^{-1} undergoes a change similar to that of CRCA. This may be attributed to the fact that the pre-soaking process increased the amount of calcium hydroxide that entered the pores of the recycled aggregate. This calcium hydroxide then reacted with carbon dioxide to produce additional calcium carbonate, resulting in an increase in the absorption peak at 1433 cm^{-1}. At the same time, the silica gel generation remained largely unaltered. In the interim, the expansion of the absorption peak at 3435 cm^{-1} suggests that the calcium hydroxide that was introduced was not entirely carbonized. This is likely due to the accelerated rate of the carbonization reaction, as the calcium carbonate that was produced occupied the pores' surface layer, thereby impeding the further progression of the carbonization reaction.

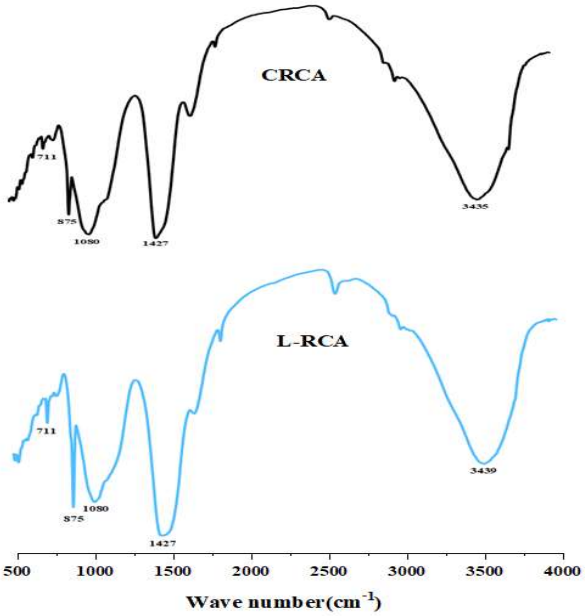


Figure 15. Infrared spectra of L-RCA after carbonization treatment.

Figure 16 illustrates the outcomes of the infrared spectroscopy measurement conducted on W-RCA (Recycled Aggregate Recycled after Ultrasonic Cavitation and then Carbonization). The absorption peak areas of W-RCA in the vibration bands of 1433 cm^{-1} and 1080 cm^{-1} were increased in comparison to CRCA; however, the increase was not statistically significant. This may be attributed to the fact that ultrasonic cavitation primarily enhances the pore structure of the recycled aggregate and increases the specific surface area, thereby enabling a greater amount of carbon dioxide to interact with the internal material. Nevertheless, the contents of calcium carbonate and silica gel increased, albeit not substantially, as a result of the limited carbonizable materials in the recycled aggregate, which impeded the deeper carbonation reaction.

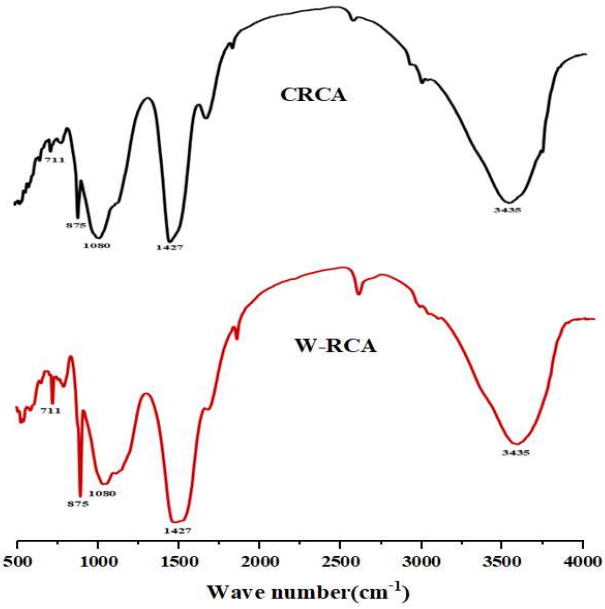


Figure 16. Infrared spectra of W-RCA after carbonization treatment.

The results of the infrared spectral analysis of carbonization of recycled aggregate after ultrasonic cavitation-pre-soaking are illustrated in Figure 17. The absorption peak area of the recycled aggregate near the 1080 cm^{-1} vibration band increased slightly under this

combination of treatments, similar to the carbonization results after ultrasonic cavitation, in comparison to the results of the single-method treatment. Conversely, the absorption peak area in the 1433 cm^{-1} vibration band increased significantly. This suggests that the pore structure was enhanced by ultrasonic cavitation, which in turn allowed for the entry of more calcium hydroxide into the pores. Consequently, the carbonation reaction generated a greater amount of calcium carbonate, which precipitated within the recycled aggregate. Consequently, the calcium carbonate content and overall performance of the recycled aggregate were enhanced.

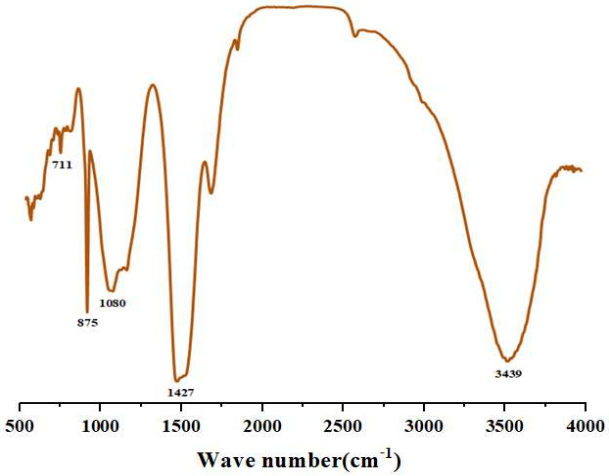


Figure 17. Infrared spectra of W-L-RCA after carbonization treatment.

3.2.3. Transition Zone Morphology of Recycled Aggregate Interface

The SEM images of aggregate–cement slurry in recycled aggregate, CRCA, L-RCA, and W-L-RCA without carbon dioxide treatment are illustrated in Figure 18. The high water absorption of recycled aggregate in the recycled aggregate mortar without carbonation treatment results in a loose structure with obvious connecting pores and a small amount of needle-like calcite. This creates a large pore size at the interface, a high water-to-cement ratio, a large space for the development of hydration products, and a non-dense distribution of calcite.

The interface transition zone is denser in the carbonized recycled aggregate mortar, as illustrated in Figure 18b, and there are no apparent connecting gaps. The pretreated carbonized recycled aggregate exhibited a denser interfacial transition zone. Carbonization decreases the water absorption of recycled aggregate, the thickness of the water film on the aggregate surface, and the pore space. Carbonization following pretreatment enhances the degree of carbonization, generates additional substances to fill the interfacial transition zone, and increases the degree of densification. The recycled aggregate's water absorption capacity is enhanced by the carbonization treatment, which guarantees that the cement surrounding the interface is completely hydrated. The microcracks adsorb cement particles, which are advantageous to the interface structure after hydration, and the difference in elastic modulus between the recycled aggregate and the fresh cement paste is reduced by the attached cement paste. Consequently, the carbonation treatment resulted in a denser interfacial transition zone in the recycled aggregate mortar.

The interfacial transition zone is enhanced, and the width is reduced following the carbonization treatment of recycled aggregate. This results in an improvement in the performance of concrete prepared with recycled aggregate and a reduction in the extension of fractures during stress.

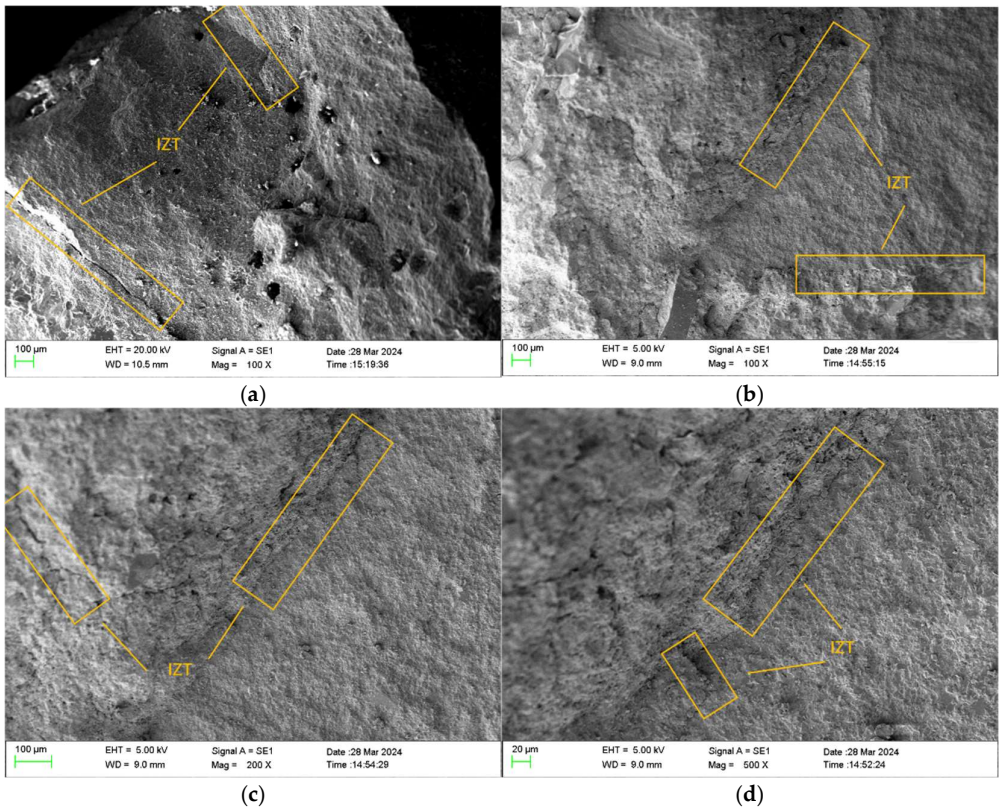


Figure 18. SEM photograph of the transition zone at the recycled aggregate interface. (**a**) CRCA; (**b**) W-RCA carbonized; (**c**) L-RCA carbonized; (**d**) W-L-RCA carbonized.

4. Discussion

In this paper, the effect of carbonization treatment on the properties of recycled aggregates was systematically investigated through experiments, aiming at exploring effective methods to enhance the application effect of recycled aggregates in concrete. In the experimental process, not only was the effect of direct carbonation on the properties of recycled aggregates investigated but also pre-treatment steps, including calcium hydroxide immersion and ultrasonic cavitation, were further introduced to explore the enhancement effect of these pre-treatment measures on the carbonation effect. In addition, this paper also explores the synergistic effects of ultrasonic cavitation and calcium hydroxide immersion treatment with a view to finding the optimal treatment combination parameters. Through this series of experiments, the following main findings were derived from this paper.

4.1. Effect of Carbonization Treatment on Physical Properties of RCA

Carbonization treatment can effectively improve the apparent density of RCA and reduce its water absorption and crushing index. Experiments showed that after carbonation treatment, the water absorption of RCA was reduced by 8.12% (14 days), 9.89% (28 days), and 9.30% (90 days) at different ages; the apparent density was increased by 2.51%, 2.82%, and 2.78%; and the crushing indexes were reduced by 6.91%, 7.61%, and 9.68%, respectively. The carbonation effect generates calcium carbonate through the reaction between carbon dioxide and cement hydration products, which fills the internal pores and cracks of aggregate, reduces the porosity and water absorption, increases the volume of hardened products, improves the apparent density, and reduces the crushing index.

4.2. Enhancement of RCA Carbonization Effect by Calcium Hydroxide Pretreatment

Calcium hydroxide pretreatment followed by carbonization further reduced the water absorption of RCA, increased its apparent density, and reduced the crushing index. Among

them, 14-day-old RCA pretreated with 0.04–0.07 mol/L calcium hydroxide concentration showed the best carbonization effect, with water absorption reduced by 13.51%, apparent density increased by 3.79%, and crushing index reduced by 15.79% compared with uncarbonized aggregate. Calcium hydroxide pretreatment increased the content of carbonizable material in the aggregate and accelerated the generation of calcium carbonate, thus filling the pores more effectively and improving the physical properties of the aggregate.

4.3. Effect of Ultrasonic Cavitation Pretreatment on the Carbonization Effect of RCA

Ultrasonic cavitation pretreatment followed by carbonization also reduced the water absorption of RCA, increased its apparent density, and reduced the crushing index. Among them, 40 W ultrasonic power had the best effect on the RCA at the age of 14 days, which reduced the water absorption by 10.71%, increased the apparent density by 3.19%, and reduced the crushing index by 10.27%. The ultrasonic cavitation promoted the carbonation reaction by optimizing the aggregate pore structure, increasing the specific surface area, and improving the contact and reaction opportunities between carbon dioxide and the internal substances of the aggregate.

4.4. Synergistic Effect of Ultrasonic Cavitation and Calcium Hydroxide Pretreatment

The combination of ultrasonic cavitation pretreatment and calcium hydroxide pretreatment followed by carbonization had the most significant effect on the improvement of RCA's physical properties. Under 0.04–0.07 mol/L calcium hydroxide concentration and 40–80 W ultrasonic power, the water absorption, apparent density, and crushing index of aggregate were effectively improved. This synergistic treatment not only optimized the pore structure of the aggregate but also increased the chemical activity on the aggregate surface, promoted the deposition of calcium carbonate, and made the aggregate structure denser.

4.5. Microstructure Analysis

XRD and infrared spectroscopy analyses showed that the content of calcium carbonate in RCA increased significantly after carbonation treatment, and calcium hydroxide pretreatment and ultrasonic cavitation pretreatment further promoted the generation of calcium carbonate. SEM scans showed that the carbonation treatment made the interfacial transition zone between RCA and cement paste denser, the connecting pores were reduced, and the aggregate and cement paste were more tightly bonded, thus improving the overall performance of recycled aggregate concrete.

5. Future Research Directions

5.1. Study of Optimized Processing Conditions

Further explore the effects of different calcium hydroxide concentrations, ultrasonic power, and treatment time on the carbonization effect of RCA in order to determine more precise and optimal treatment conditions. To study the applicability and effect differences of different sources and types of recycled construction waste aggregates in carbonization treatment in order to provide broader technical support for large-scale applications.

5.2. Long-Term Performance and Durability Studies

Long-term monitoring of physical property changes of carbonation-treated RCA under different environmental conditions to assess its long-term stability and durability. To study the effect of carbonation treatment on the performance of recycled aggregate concrete in harsh environments such as freeze–thaw cycles and chemical corrosion and to expand its application in special engineering fields.

5.3. Integration Studies with Other Technologies

Explore the combination of carbonation technology with other pretreatment methods, such as mechanical activation and chemical modification, to further improve the performance of RCA. Study the synergistic effect of carbonation treatment with other admixtures (e.g., fly ash, slag) in recycled aggregate concrete to optimize the concrete proportion design and improve its comprehensive performance.

5.4. Environmental Benefits and Economic Cost Analysis

Evaluate in detail the environmental benefits of the carbonization treatment technology in the application of recycled aggregates, including the amount of CO_2 fixation, the amount of resource-saving, and the positive impact on the ecological environment. Analyze the economic costs of different treatment processes, including raw material costs, equipment input, and energy consumption, to provide an economic basis for the promotion and application of the technology.

In summary, this paper reveals the effectiveness and microscopic mechanism of carbonation treatment on the performance enhancement of recycled coarse aggregate through systematic experimental research, which provides theoretical support and technical guidance for the efficient application of recycled aggregate in concrete. Future research will further optimize the treatment process, expand the scope of application, and evaluate its environmental and economic benefits in depth so as to promote the resourceful utilization of construction waste and sustainable development.

Author Contributions: Conceptualization, M.L. and X.L.; methodology, M.L.; software, M.L.; validation, M.L., X.L. and M.W.; formal analysis. X.L.; investigation, M.W.; resources, M.L.; data curation, X.L.; writing—original draft preparation, M.W.; writing—review and editing, X.L.; visualization, X.L.; supervision, Q.X.; project administration, Q.X.; funding acquisition, M.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the "Open Fund Project of the High-Speed Railway Engineering Technology Research Center", with the project number (TTKF2022-03), and the article processing fee was also provided by the "Open Fund Project of the High-Speed Railway Engineering Technology Research Center".

Data Availability Statement: The authors confirm that the data supporting the findings of this study are available within the article.

Conflicts of Interest: Author Mingqiang Lin is employed by the Shandong Railway Investment Holding Group Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

1. Huang, L.; Krigsvoll, G.; Johansen, F.; Liu, Y.; Zhang, X. Carbon emission of global construction sector. *Renew. Sustain. Energy Rev.* **2018**, *81*, 1906–1916. [CrossRef]
2. Rao, A.; Jha, K.N.; Misra, S. Use of aggregates from recycled construction and demolition waste in concrete. *Resour. Conserv. Recycl.* **2006**, *50*, 71–81. [CrossRef]
3. Annual report on the comprehensive utilization of resources in China. *Recycl. Resour. Circ. Econ.* **2014**, *7*, 3–8.
4. China Building Materials Industry Carbon Emission Report. *China Build. Mater.* **2021**, *64*, 59–62. [CrossRef]
5. Akhtar, A.; Sarmah, A.K. Construction and demolition waste generation and properties of recycled aggregate concrete: A global perspective. *J. Clean. Prod.* **2018**, *186*, 262–281. [CrossRef]
6. Xiao, J.; Ma, Z.; Sui, T.; Akbarnezhad, A.; Duan, Z. Mechanical properties of concrete mixed with recycled powder produced from construction and demolition waste. *J. Clean. Prod.* **2018**, *188*, 720–731. [CrossRef]
7. Tian, J. Comprehensive Benefit Analysis of Recycled Aggregate Produced by Construction Waste. Master's Thesis, Chongqing University, Chongqing, China, 2019.

8. Gluzhge, P. The work of scientific research institute. *Gidrotekhnicheskoye Stroit.* **1946**, *4*, 27–28.
9. ABE Michihiko. Efficient use of construction by-products. *Civ. Constr.* **1995**, *36*, 7–9.
10. Juan MS, D.; Gutiérrez, P.A. Study on the influence of attached mortar content on the properties of recycled concrete aggregate. *Constr. Build. Mater.* **2008**, *23*, 872–877. [CrossRef]
11. Li, J.; Xiao, J.; Sun, Z. Properties of Recycled Coarse Aggregate and Its Influence on Recycled Concrete. *J. Build. Mater.* **2004**, *7*, 390–395.
12. Kou, S.C.; Poon, C.S. Enhancing the durability properties of concrete prepared with coarse recycled aggregate. *Constr. Build. Mater.* **2012**, *35*, 69–76. [CrossRef]
13. Quan, H.; Ding, J.; Zhu, Y.; Yang, X.; Li, Q. Experimently Study on Effects of Different Properties of Recycled Coarse Aggregates on Strengths and Durability of Concrete. In Proceedings of the 1st Symposium on Research and Application of Recycled Concrete in P.R. China, Shanghai, China, 18–19 July 2008.
14. Zhang, J. The Characteristics of Mechanical Properties of Recycled Aggregate Concrete and Influencing Factor. Master's Thesis, Beijing Jiaotong University, Beijing, China, 2010.
15. Lei, B.; Xiao, J. Research on Carbonation Resistance of Recycled Aggregate Concrete. *J. Build. Mater.* **2008**, *11*, 605–611.
16. Ding, Y.; Wu, J.; Xu, P.; Zhang, X.; Fan, Y. 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]
17. Xiao, J.; Liu, Q.; Li, W.; Vivian, T. On the Micro-and Meso-Structure and Failure Mechanism of Recycled Concrete. *J. Qingdao Technol. Univ.* **2009**, *30*, 24–30.
18. Leite, M.B.; Monteiro, P.J.M. Microstructural analysis of recycled concrete using X-ray microtomography. *Cem. Concr. Res.* **2016**, *81*, 38–48. [CrossRef]
19. Wu, J.; Zhang, Y.; Zhu, P.; Feng, J.; Hu, K. Mechanical Properties and ITZ Microstructure of Recycled Aggregate Concrete Using Carbonated Recycled Coarse Aggregate. *J. Wuhan Univ. Technol. -Mater. Sci. Ed.* **2018**, *33*, 648–653. [CrossRef]
20. 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]
21. Cheng, X.; Lin, Z.; Ren, P. Review of CO_2 curing for concrete and recycled concrete. *Concrete* **2020**, *42*, 156–160.
22. Yuan, C.; Niu, D.; Chen, N.; Duan, F. Effect of carbonation on the microstructure of concrete. *Bull. Chin. Ceram. Soc.* **2013**, *32*, 687–691+707. [CrossRef]
23. Kuang, T. Effect of Carbonization on Microstructure of Recycled Concrete. Master's Thesis, Southeast University, Nanjing, China, 2018.
24. Tang, W. Research on Key Technology of Utilization of Recycled Concrete Aggregate to Sequestrate CO_2. Master's Thesis, Shenzhen University, Shenzhen, China, 2019.
25. Kou, S.-C.; Zhan, B.-J.; Poon, C.-S. Use of a CO_2 curing step to improve the properties of concrete prepared with recycled aggregates. *Cem. Concr. Compos.* **2014**, *45*, 22–28. [CrossRef]
26. 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]
27. Fang, X.; Zhan, B.; Poon, C.S. Enhancement of recycled aggregates and concrete by combined treatment of spraying Ca2+ rich wastewater and flow-through carbonation. *Constr. Build. Mater.* **2021**, *277*, 122202. [CrossRef]
28. Shi, C.; Wu, Z.; Cao, Z.; Ling, T.C.; Zheng, J. Performance of mortar prepared with recycled concrete aggregate enhanced by CO_2 and pozzolan slurry. *Cem. Concr. Compos.* **2018**, *86*, 130–138. [CrossRef]
29. Li, Y.; Fu, T.; Wang, R.; Li, Y. An assessment of microcracks in the interfacial transition zone of recycled concrete aggregates cured by CO2. *Constr. Build. Mater.* **2020**, *236*, 117543. [CrossRef]
30. Wang, J.; Zhang, J.; Cao, D.; Dang, H.; Ding, B. Comparison of recycled aggregate treatment methods on the performance for recycled concrete. *Constr. Build. Mater.* **2020**, *234*, 117366. [CrossRef]
31. Li, L.; Poon, C.S.; Xiao, J.; 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]
32. Ying, J.; Meng, Q.; Xiao, J. CO_2 strengthening of recycled aggregate and its influence on compressive strength of concrete. *J. Build. Mater.* **2017**, *20*, 277–282.
33. Luo, S.; Ye, S.; 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]
34. Ding, J. Effects of the replacement ratio of carbonized recycled fine aggregate on the compressive strength of recycled concrete. *J. Fujian Univ. Technol.* **2019**, *17*, 13–16.
35. Medina, C.; Zhu, W.; Howind, T.; de Rojas, M.I.S.; Frías, M. Influence of mixed recycled aggregate on the physical—Mechanical properties of recycled concrete. *J. Clean. Prod.* **2014**, *68*, 216–225. [CrossRef]
36. Tam VW, Y.; Butera, A.; Le, K.N. Carbon-conditioned recycled aggregate in concrete production. *J. Clean. Prod.* **2016**, *133*, 672–680. [CrossRef]

37. Kazmi, S.M.; Munir, M.J.; Wu, Y.F.; Patnaikuni, I.; Zhou, Y.; Xing, F. Influence of different treatment methods on the mechanical behavior of recycled aggregate concrete: A comparative study. *Cem. Concr. Compos.* **2019**, *104*, 103398. [CrossRef]
38. 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]
39. *GB175-2007*; Universal Silicate Cement. General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China, Standardization Administration of China: Beijing, China, 2007.
40. *GB/T14684-2001*; Construction Sand. General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China, Standardization Administration of China: Beijing, China, 2001.
41. *JGJ52-2006*; Standard for Quality and Test Method of Sand and Stone for Ordinary Concrete. Ministry of Construction of the People's Republic of China: Beijing, China, 2006.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.