

Article

A Study of the Self-Healing Mechanism of Concrete Using Microorganisms Immobilized in an Improved Recycled Aggregate

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Abstract

This study was conducted to determine the optimal mineralization enhancement period for recycled aggregates, and to elucidate the mechanisms underlying the mineralization enhancement of recycled aggregates and the self-healing of concrete cracks. Microbial-induced calcium carbonate precipitation enables the self-healing of concrete cracks: microbial carriers can effectively increase the survival rate of microorganisms within the concrete matrix, thereby enhancing the self-healing performance of the concrete. However, current carriers suffer from poor mechanical properties, poor compatibility with cement-based materials, and high costs. This study proposed a crack-self-healing concrete based on a mixed culture of microorganisms immobilized in recycled aggregate, and investigated the effects of the time of recycled aggregate incorporation on the concrete's compressive strength and self-healing performance. The results showed that the optimal adsorption and incubation times for the recycled aggregates were 15 min and 9 days, respectively. Following mineralization and reinforcement, the water absorption and crushing index of the recycled aggregates was 11.4% and 20.4%, respectively. Moreover, the precipitates at the concrete cracks were in the form of regular cubes and clusters, and the crystals were calcite and aragonite. Small amounts of phosphorus were detected, originating from extracellular polymers produced by microbial metabolism, indicating that the organic matrix was involved in the crystal nucleation and growth processes. The compressive strength of the concrete increased by 35%. After repair and curing, the crack healing rate of the concrete reinforced with microorganisms immobilized on the recycled aggregates reached 70%.

Keywords: biomineralization; reinforced recycled aggregates; concrete; repair mechanism; compressive strength; water absorption; crushing index



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1. Introduction

Due to their anisotropic and heterogeneous nature, concrete structures develop microcracks during service life as a result of factors such as loads and temperature [1,2]. These cracks provide pathways for harmful ions (chloride and sulfate ions) to penetrate the concrete, leading to concrete deterioration and reinforcement corrosion, which compromise the safety and durability of the concrete structure. The primary hazards posed by cracking lie in their ability to weaken a structure's load-bearing capacity, accelerate rebar corrosion, shorten the structure's service life, and cause water leakage and functional failure. Economic losses include direct repair and reinforcement costs, construction delays,

asset depreciation, and potential compensation claims; in severe cases, they can result in the entire building being declared a total loss or lead to massive joint liability claims [3]. The self-healing technology for concrete cracks based on microbial mineralization utilizes the metabolic activity of microorganisms to mineralize and deposit calcium carbonate, thereby enabling the self-healing of concrete cracks [4]. Due to its environmentally friendly repair process and the excellent compatibility of the mineralized deposits with cementitious materials, this technology has attracted significant research interest from many scholars. When microorganisms are added directly to concrete, factors such as the highly alkaline internal environment and reduced living space can lead to a significant decrease in the number of viable bacteria, thereby affecting the self-healing performance of cracks. Therefore, most current studies employ porous materials and encapsulation materials to immobilize microorganisms within the concrete matrix, such as expanded perlite, microcapsules, and ceramic aggregates [5,6].

These carriers have poor physical and mechanical properties, are not very compatible with cement-based materials, and are relatively expensive, making them difficult to implement in engineering applications. Compared to the aforementioned materials, recycled aggregates offer superior physical properties, compatibility, and significant cost advantages [7,8]. Additionally, the porous old cement mortar and microcracks adhering to the surface of recycled aggregates provide a suitable environment for microbial growth and metabolism. Therefore, they can be used to immobilize microorganisms for the preparation of self-healing concrete. Shen et al. prepared self-healing concrete by immobilizing *Bacillus subtilis* on recycled aggregates; after 28 days of curing, the average crack repair width reached 0.28 mm [9]. Zou et al. used a vacuum method to immobilize a self-selected mixed culture of aerobic and alkalophilic bacteria onto defects in recycled aggregates. The self-healing concrete prepared in this manner achieved a maximum crack repair width of 0.57 mm after 28 days of water curing [10]. However, the inherent defects in recycled aggregates can affect the workability and mechanical properties of concrete, and the interface transition zone is relatively weak. Therefore, some researchers have developed self-healing concrete by reinforcing recycled aggregates with immobilized microorganisms [11,12]. Wang et al. used microorganisms immobilized on recycled aggregates to prepare self-healing concrete, resulting in a 12.9% increase in compressive strength and a 20% increase in slump; compared with ordinary concrete, the average crack repair width and complete closure rate increased by 47.4% and more than 50%, respectively [13]. However, researchers have not yet determined a reasonable duration for the incorporation of recycled aggregates based on the influence of this duration on the mechanical properties and self-healing performance of concrete [14,15].

This paper describes the preparation of crack-self-healing concrete using a mixture of microorganisms immobilized in reinforced recycled aggregates, effectively addressing issues such as the poor mechanical properties of microbial carriers, high costs, and poor compatibility with cement-based materials. By investigating the effects of the curing time of recycled aggregates on the compressive strength and self-healing properties of concrete, this study determines an optimal curing time for recycled aggregates to ensure that the concrete possesses both good mechanical properties and a certain degree of crack self-healing capability. SEM and XRD analyses are employed to elucidate the mechanisms underlying the reinforcement effect of recycled aggregates and the self-healing of concrete cracks. By investigating the effects of the mineralization enhancement period of recycled aggregates on the compressive strength and self-healing properties of concrete, this study identifies an optimal mineralization enhancement period for recycled aggregates and elucidates the mechanisms underlying the mineralization enhancement of recycled aggregates and the self-healing of concrete cracks.

2. Materials and Methods

2.1. The Process of Self-Healing in Concrete Cracks

Self-healing concrete was prepared using recycled aggregates reinforced with immobilized microorganisms. Specifically, the recycled aggregates were first enhanced through mineralization before being used to prepare the self-healing concrete. Defects on the surface of the recycled aggregates were filled and covered by precipitate crystals, thereby improving the mechanical properties of the aggregates to enhance both the workability and mechanical performance of the self-healing concrete. Furthermore, the precipitate layer on the surface of the recycled aggregates provided additional protection for the microorganisms against the harsh environment within the concrete matrix; when cracks form in the concrete matrix, water and air enter the cracks, triggering the microorganisms immobilized in the reinforced recycled aggregates to begin mineralizing and depositing calcium carbonate to fill the concrete cracks, thereby achieving self-healing, as shown in Figure 1.

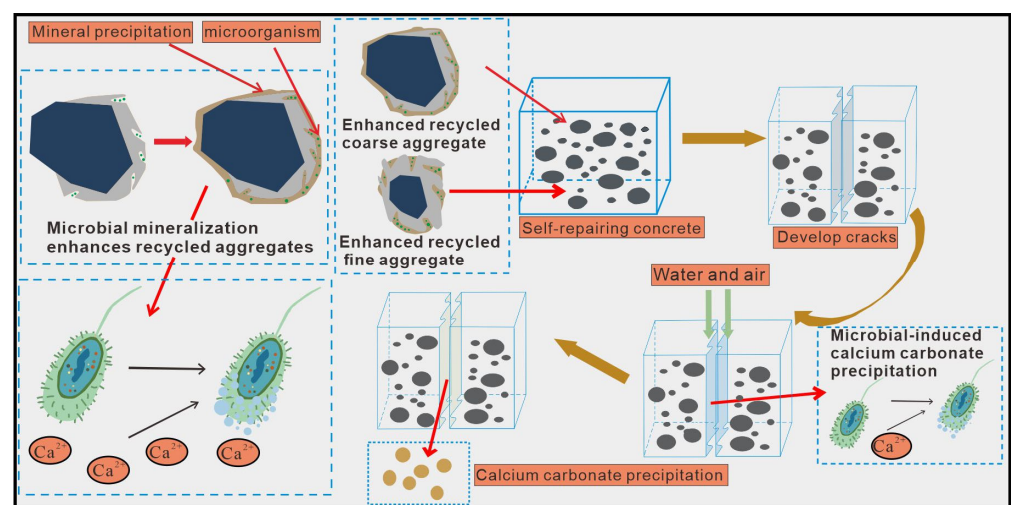


Figure 1. Principle diagram of crack-self-repairing concrete.

2.2. Description of Microorganisms and Culture Media

The microorganisms used were a mixed culture of aerobic, alkali-loving bacteria that we screened ourselves. We used activated sludge from a wastewater treatment plant in Suzhou City, Anhui Province, and garden soil as microbial sources, and enriched and screened the culture over 12 cycles using lactic acid as a substrate under alkaline, aerobic conditions [16,17]. After screening, the mixed microbial cultures were preserved in glycerol at -80°C . The aerobic basophilic mixed microbial cultures selected through our own screening were chosen as mineralizing microorganisms because they exhibit high mineralization efficiency, excellent mineralization robustness, and significant economic benefits. The target mixed culture synergistically induces calcium carbonate precipitation through material exchange and electrochemical signaling between microbial communities. Previous studies have shown that the inorganic carbon conversion rate of this mixed culture can reach over 70%.

Aerobic basophilic mixed cultures consist of microbial communities with various morphologies, including rod-shaped and spherical forms. This indirectly confirms that, unlike the mechanism by which pure cultures induce calcium carbonate precipitation, aerobic basophilic mixed cultures mineralize and deposit calcium carbonate through the synergistic action of multiple microbial colonies. The cultivation process for aerobic basophilic mixed cultures follows standard inoculation and culture methods for aerobic microorganisms [18,19]. The culture medium used contains 10 g of sodium chloride, 10 g

of tryptone, and 5 g of yeast extract per liter of solution, with the pH adjusted to 7.0 using a 2 mol/L NaOH solution. After culturing for 2 days in a constant-temperature shaking incubator at 33 °C and 130 rpm, the culture was centrifuged to obtain a bacterial slurry. The slurry was then resuspended in a 5 g/L solution of sterile yeast extract to an OD₆₀₀ value of 1.2 and set aside for later use.

2.3. Process for Reinforcing with Recycled Aggregates

Construction waste was sorted manually or mechanically to remove impurities such as rebar, wood, plastic, and soil, and light materials. Metals were separated using methods such as magnetic separation and air classification. A multi-stage crushing process was employed, utilizing a jaw crusher (primary crushing), an impact or cone crusher (secondary crushing), and a vertical shaft impact crusher (tertiary crushing and shaping), to reduce large chunks of waste concrete to the appropriate particle size (typically 0–40 mm). The material was separated by particle size using a vibrating screen, with particles larger than 4.75 mm classified as recycled coarse aggregate and those smaller than 4.75 mm as recycled fine aggregate. Next, water washing or air separation was used to remove cement mortar, mud, and dust adhering to the surface, thereby improving cleanliness and performance. The process for strengthening recycled aggregates was as follows. Place the recycled aggregates in a vacuum chamber and use a vacuum pump to reduce the pressure inside the chamber to -0.06 MPa. Utilize the pressure difference to adsorb the prepared bacterial suspension into the chamber, maintaining the adsorption for varying durations at a pressure of -0.06 MPa. Then, the recycled aggregate loaded with microorganisms is removed and placed in a 65 g/L calcium lactate solution (pH adjusted to 7.0 with NaOH). The primary reason for using calcium lactate as a nutrient was that, on the one hand, it provided the calcium ions required for calcium carbonate precipitation. On the other hand, the lactate ions serve as nutrients that stimulate microbial metabolism to induce carbonate precipitation. To ensure enhanced microbial mineralization, oxygen was introduced into the nutrient solution to maintain a constant dissolved oxygen concentration and keep the solution temperature stable. The regenerated aggregate was then removed at a predetermined time.

2.4. Preparation of Self-Healing Concrete

The cement used was 42.5-grade ordinary Portland cement from a cement plant in Suzhou City, and the sand was ordinary river sand from a plant in Suzhou City, with a silt content of 0.3%. The water-reducing agent was a polycarboxylate high-performance water-reducing agent, and the water was distilled water. The admixture was calcium lactate, and the mix design is shown in Table 1. The mix proportion of the cement content was 200 kg/m³. In fact, this mixture can represent only laboratory mortar or concrete for self-healing evaluation. For structural concrete, this mix proportion should be adjusted according to the actual conditions.

In the experimental groups, recycled aggregates were mixed with mixed bacteria for 5, 10, 15, and 20 min, respectively, based on the control group, and then strengthened for 3, 6, 9, and 12 days, respectively, to serve as microbial carriers. The experimental groups were designated as groups S-Z3, S-Z6, S-Z9, and S-Z12 (S-Z3, S-Z6, S-Z9, and S-Z12 indicated that the strengthening periods were 3, 6, 9, and 12 days, respectively). Calcium lactate solution was used as the mixing water for all specimens. The specimens used to test the self-healing effect of concrete cracks were cylinders with a diameter of 100 mm and a height of 50 mm, while those used to test the compressive strength of self-healing concrete were cubes with a side length of 100 mm; three specimens were prepared for each group. After mixing, the concrete was poured into molds, left to set for 48 h, demolded, and then cured for 28 days under standard conditions of (20 ± 2) °C and 95% humidity. The control

group followed the same treatment steps and added the same proportion of the mixture (as shown in Table 1), except that an equal volume of distilled water was used in place of the microbial culture.

Table 1. Mixing proportion of the self-healing concrete.

Number	Mix Proportion (kg/m ³)						
	Recycled Coarse Aggregate	Sand	Recycled Fine Aggregate	Cement	Water	Water Reducer	Calcium Lactate
Control Group	500	200	80	200	100	1.8	4.8
S-Z3	500	200	80	200	100	1.8	4.8
S-Z6	500	200	80	200	100	1.8	4.8
S-Z9	500	200	80	200	100	1.8	4.8
S-Z12	500	200	80	200	100	1.8	4.8

2.5. Testing of Self-Healing Properties in Concrete Cracks

To investigate the effects of mixed-bacterial adsorption and mineralization duration on the water absorption rate, crushing index, and self-healing properties of recycled aggregates, the aggregates were placed in an oven at 105 °C and dried to constant weight 3, 6, 9, and 12 days after mineralization. The water absorption rate and crushing index of the recycled aggregates were then tested [20,21]. The formulas are shown below:

$$W = \frac{m_1 - m_2}{m_1} \times 100\% \quad (1)$$

W is the water absorption, m_1 is the mass of the saturated surface dry sample, and m_2 is the mass of the dried sample.

$$C = \frac{G_1 - G_2}{G_1} \times 100\% \quad (2)$$

C is the crushing index, G_1 is the mass of the sample, and G_2 is the residual mass after the crushing test.

After 28 days of curing, the self-healing concrete was tested for compressive strength. Additionally, crack observation points were marked at 1 cm intervals along the crack direction. Approximately 12 cracks with initial widths ranging from 0.3 to 1.5 mm were selected as self-healing monitoring points for each test group. The specimens were then placed in water for immersion curing, and the crack healing progress was observed at 7, 14, 21, and 28 days after repair. The effectiveness of crack self-healing was evaluated using the crack healing rate (H_P), as shown in the following formula:

$$H_P = \frac{W_0 - W_t}{W_0} \times 100\% \quad (3)$$

W_t is the remaining crack width, and W_0 is the initial crack width [22].

2.6. X-Ray Diffraction (XRD) Analysis

The precipitates at the cracks in the repaired concrete were analyzed by X-ray diffraction (XRD, Bruker D8 Advance, Ettlingen, Germany). Powder samples must be thoroughly ground to a particle size of 300–320 mesh (approximately 40 µm). A sample weight of at least 0.2 g was recommended. For standard sample preparation, clean the microscope slide with alcohol, spread the powder evenly, and press it flat to ensure the sample surface

is flush with the slide. For the tape-pressing method, aluminum foil and double-sided tape were used to ensure the sample was thin and uniform. The detector mode and scan type were set to continuous coupling scan. The default scan range for conventional phase analysis was $10\text{--}70^\circ$, with a scan speed of $4^\circ/\text{min}$ and a step size of 0.02° [23]. After completing the settings, the parameters were saved and the file save path and sample name were confirmed.

2.7. Scanning Electron Microscopy (SEM) and Energy-Dispersive Spectroscopy (EDS)

To further analyze the microstructure and element distribution of the precipitates at the cracks in the repaired concrete, SEM and EDS (TESCAN MIRA4, TESCAN, Czech Republic) were used for observation. The sample was placed flat on the conductive adhesive and secured to the sample stage. The electron beam was turned on, an appropriate acceleration voltage ($10\text{--}20\text{ kV}$ for routine analysis, $5\text{--}10\text{ kV}$ for light elements, and 20 kV or higher for heavy elements) was selected, and the beam was set to current parameters. The electron beam was positioned on the target analysis point, energy spectrum acquisition was begun, and the system was allowed to automatically perform qualitative and quantitative elemental analysis [24]. Three parallel points were sampled and averaged.

3. Results and Discussion

3.1. Water Absorption and Crushing Index of Enhanced Recycled Concrete Aggregate

Figure 2 shows the water absorption of recycled aggregates after different adsorption and strengthening periods using microbial mixtures. The experimental results indicated that the water absorption exhibited a trend of first decreasing and then increasing as the adsorption and strengthening periods were extended. After 9 days of mineralization strengthening, the water absorption of the recycled aggregates reached a minimum of 11.4%, whereas the water absorption of the control group was 25.8%. When the strengthening period exceeded 9 days, the water absorption of the recycled aggregates increased.

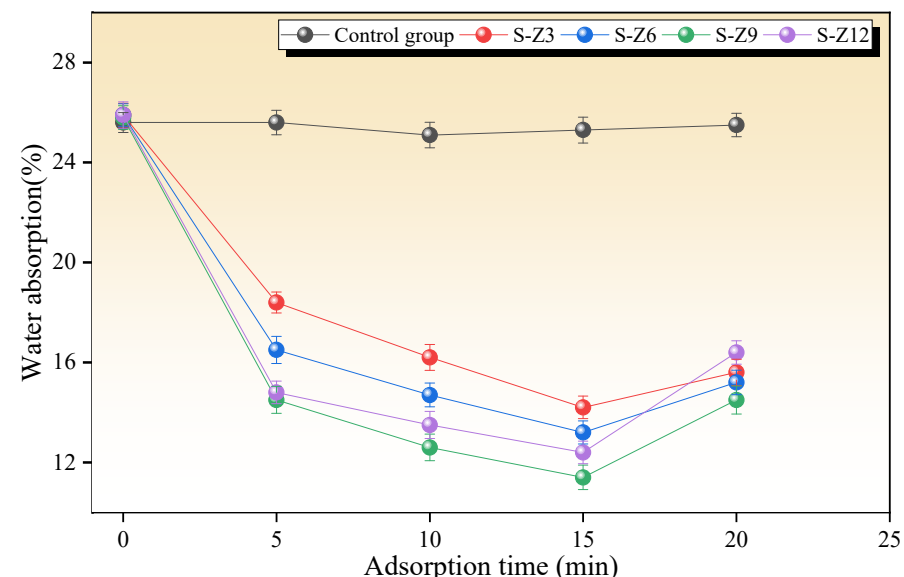


Figure 2. The water absorption rate of enhanced recycled concrete aggregate influenced by different mineralization and adsorption time.

Figure 3 shows the crushing index of recycled aggregates after different adsorption and strengthening periods using mixed microorganisms. The experimental results indicated that the crushing index exhibited a similar trend. After 9 days of mineralization strengthening, the crushing index of the recycled aggregates was 20.4%, whereas the crushing index of the

control group was 50.1%. When the strengthening period exceeded 9 days, the crushing index of the recycled aggregates increased.

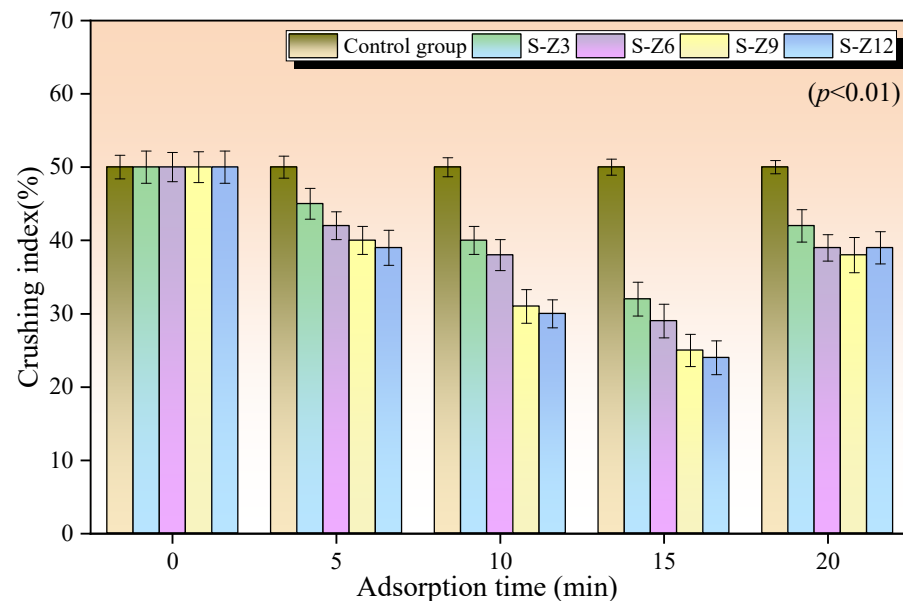


Figure 3. The crushing index of enhanced recycled concrete aggregate influenced by different mineralization and adsorption time. Double asterisk means $p < 0.01$, indicating that the results have statistical significance. $p < 0.01$ indicating that the results have statistical significance.

This may be because, in the early stages of reinforcement, microorganisms deposited mineralized precipitates in the microcracks and voids of the recycled aggregate and old cement mortar to repair defects; at this stage, the microbial population was large, and the arrangement of precipitate crystals was relatively dense [25,26]. As the reinforcement period extended, the microorganisms were gradually encapsulated by the mineralized precipitate crystals they produced, leading to a decrease in the microbial population. Subsequently, the arrangement of mineralized precipitate crystals became relatively loose, forming new voids, which manifested macroscopically as increases in water absorption and crushing index.

3.2. Phase Analysis of Mixed-Bacterial Mineralized Precipitates

In this analysis, X-ray diffraction (XRD) was used to characterize the calcium carbonate precipitates induced by the microorganisms shown in Figure 4, thereby identifying the crystal phase composition and characteristic diffraction peaks. The XRD peak intensity at 2θ in the control group was 29.40° , which matched well with the peak of pure calcite. The remaining peaks were essentially consistent with those of pure calcite, indicating that the mixed-bacterial mineralization precipitates on the surface of the recycled aggregate are calcite-type calcium carbonate. The XRD spectrum of the precipitates from the experimental group (S-Z3, S-Z6, S-Z9 and S-Z12) showed that the strongest peak at 2θ was 29.43° , which corresponded well with the strongest peak in the XRD spectrum of pure calcite; among the other peaks, the peak labeled Cc matched the calcite spectrum. The peak labeled Ae also matched well with the strongest peak in the XRD spectrum of pure aragonite, indicating that the mixed-bacterial mineralization precipitates in the fracture zone consist of calcite-type and aragonite-type calcium carbonate.

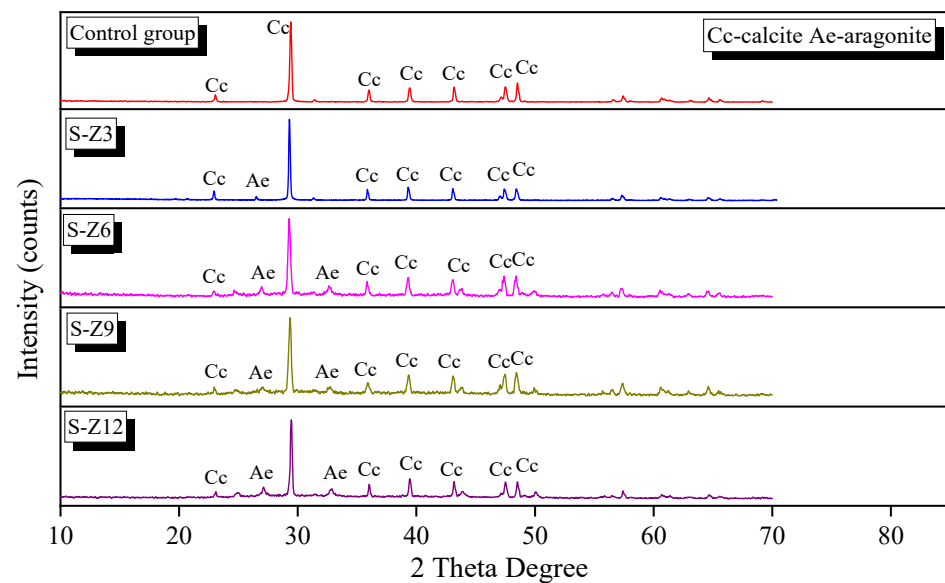


Figure 4. XRD spectra of the precipitates at the cracks in the repaired concrete.

Existing research indicates that microbial types and environmental conditions jointly determine the composition of precipitated crystal phases. An analysis of surface sediments in caves revealed that the primary mineral components of naturally mineralized precipitates were magnesium calcite and aragonite. In soil, quartz and magnesium calcite predominate. Specific isolation and culture experiments showed that only calcite and sphalerite were detected in standard culture media (without added Mg^{2+}). Conversely, aragonite was not detected in media supplemented with Mg^{2+} , indicating that indigenous microorganisms in this environment do not induce the precipitation of aragonite. Some functional strains can specifically induce aragonite precipitation; for example, they can produce aragonite-type calcium carbonate during the biological reinforcement of tropical limestone [27]. *Bacillus amyloliquefaciens* can simultaneously promote the formation of both calcite and aragonite crystal forms. Differences in pH, oxygen levels available to microorganisms, nutrient levels, and nucleation sites between areas of microcracks and voids in recycled aggregate and old cement mortar, as well as areas of cracks in the concrete matrix, result in variations in the types of calcium carbonate crystals formed. When using microbial-induced carbonate precipitation technology to enhance the performance of recycled concrete aggregates, XRD analysis revealed that the precipitates consist primarily of calcite with a small amount of aragonite; the dense layer of calcium carbonate effectively seals the pores in the aggregates, thereby improving the self-healing performance [28].

3.3. Microstructure of Mixed-Bacterial Mineralized Precipitates

Figure 5 shows SEM images of the mixed-bacterial mineralization precipitates at the concrete crack sites. The SEM analysis reveals that, in the control group without mixed-bacterial reinforcement treatment, the concrete exhibited obvious defects such as microcracks and voids, as shown by the red circle in Figure 5a,d,g,j. After microbial reinforcement treatment, the defects in the concrete cracks were filled and covered by square and rhombohedral crystals, as shown by the red arrow in Figure 5e,k. Most rhombohedral crystals had a particle size of 5–10 μm ; individual crystals aggregated and connected with cement hydration products to form larger crystal clusters (Figure 5f–l). Furthermore, as the mineralization treatment time increased, the precipitate crystals distributed uniformly and accumulated densely, effectively repairing the cracks in the concrete and significantly improving its mechanical properties. Traces of microbial growth, reproduction, and mineralization deposition were visible on the surfaces of the precipitate crystals.

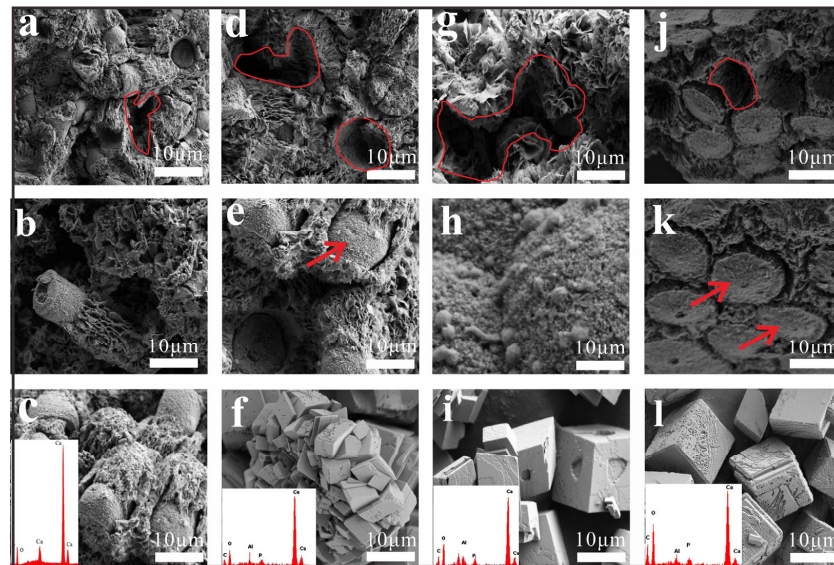


Figure 5. SEM images of the precipitates at the cracks in the repaired concrete: (a–c), SEM images of the precipitates in the control group; (d–f), SEM images of the precipitates after 7 days; (g–i), SEM images of the precipitates after 14 days; (j–l), SEM images of the precipitates after 28 days.

The major elements in the crystals of the control group were C, O, and Ca, with an atomic ratio of Ca:(C:O) close to 1:1:3, consistent with the elemental composition of calcium carbonate (CaCO_3). No distinct peaks characteristic of other impurity elements were observed, as seen in Figure 5c. Small amounts of phosphorus (approximately 1.2–1.8% by atomic weight) were detected in all crystals from the experimental group, originating from extracellular polymers (EPs) produced by microbial metabolism, indicating that the organic matrix was involved in the crystal nucleation and growth processes (Figure 5f–l).

Microbial-induced calcium carbonate precipitation (MICP) is a current research focus in the field of biomineralization [29,30]. This process has been widely applied in soil stabilization, heavy metal contamination remediation, and the self-healing of concrete cracks. The microstructure, crystal size, and degree of crystallization of the precipitates directly determine the engineering properties and environmental stability of the mineralization products. Among these, square and rhombohedral crystals were typical crystal structures in MICP products and contribute most significantly to the cementation process. Based on existing XRD findings, the square and rhombohedral products observed in this SEM analysis were all calcite-type calcium carbonate, which was the most thermodynamically stable crystal form in microbe-induced calcium carbonate precipitation. In engineering applications, these crystals can more effectively fill particle pores and enhance the strength of the cemented matrix. In heavy metal remediation scenarios, highly crystalline calcite can more stably coprecipitate and immobilize heavy metal ions, thereby reducing the risk of heavy metal re-release. Aragonite, as an intermediate product of the crystallization process, will dissolve and recrystallize into stable calcite given sufficient reaction time [31].

3.4. Analysis of the Self-Healing Effect of Concrete Cracks

Figure 6 shows the appearance of cracks in concrete after different repair durations. As shown in Figure 6a–c, after 28 days of repair, the cracks in the control group were only partially repaired. This was because unhydrated cement particles came into contact with water and underwent further hydration, thereby repairing the cracks; however, this self-healing capacity was limited. Cracks in the S-Z3, S-Z6, S-Z9 and S-Z12 groups of self-healing concrete containing microorganisms were repaired by being filled with precipitates, as seen in Figure 6d–o. During the initial activation phase, scattered white, dot-like precipitates

appear along the edges of the crack, while the main body of the crack remains clearly visible and shows no significant narrowing in width. At this stage, water and oxygen infiltrate the crack, activating dormant microorganisms. The microorganisms have just begun metabolic activity, generating only a small amount of calcium carbonate crystal nuclei on the crack surface; a continuous deposit layer has not yet formed. From the surface image, it can be observed that the coverage of white precipitates is less than 10%, distributed only sporadically along the crack walls. The overall crack outline remains intact, with no visible signs of closure, and water seepage is still clearly observable during water permeability tests. In the second stage—the rapid deposition stage—continuous bands of calcium carbonate deposits begin to form along the crack edges. The crack width narrows from an initial 0.3–0.4 mm to 0.1–0.2 mm, and approximately 30–40% of the crack area is filled with precipitates. At this stage, microorganisms enter a period of active metabolism, and calcium carbonate crystals continue to grow and aggregate, gradually advancing from the crack edges toward the center. In the surface image, a noticeable lightening of the crack outline can be observed; unfilled gaps remain visible in the central area, with only partial sections of the crack achieving surface closure. The color of the deposition area is significantly lighter than that of the surrounding concrete matrix, creating a grayish-white contrast. In the third stage, approaching the closure phase, for cracks with an initial width of 0.3–0.4 mm, the apparent healing rate reaches approximately 90%. Only a few crack segments retain extremely fine, visible gaps, while cracks in most areas are virtually indistinguishable to the naked eye, and the area covered by calcium carbonate deposits exceeds 85%. At this stage, microorganisms continue to metabolize and produce calcium carbonate, gradually filling the cracks from the surface to the depths. Only a small amount of unfilled gaps remain at crack intersections or wider sections. In the surface image, the color of the deposited areas gradually approaches that of the base concrete, with only a slight color difference, and the overall crack lines have essentially disappeared.

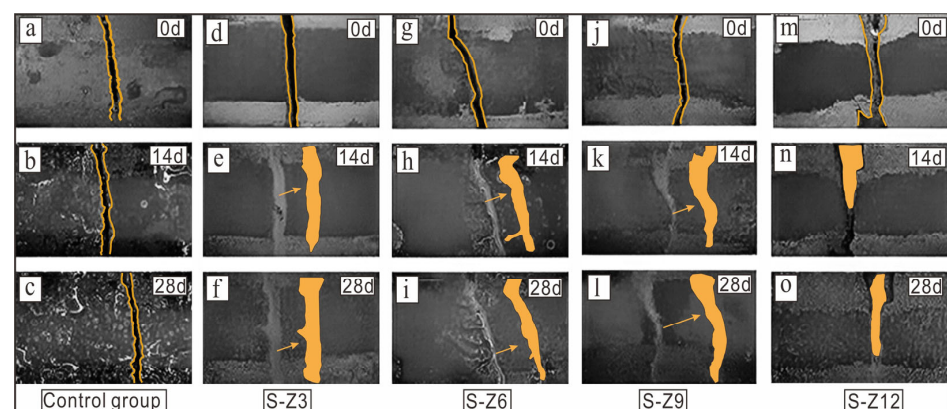


Figure 6. Visual diagram of the self-repair process of concrete cracks: (a–c), images of the concrete cracks in the control group after curing periods of 7, 14, and 28 days; (d–f), images of the concrete cracks in the S-Z3 group after curing periods of 7, 14, and 28 days; (g–i), images of the concrete cracks in the S-Z6 group after curing periods of 7, 14, and 28 days; (j–l), images of the concrete cracks in the S-Z9 group after curing periods of 7, 14, and 28 days; (m–o), images of the concrete cracks in the S-Z12 group after curing periods of 7, 14, and 28 days.

Specifically, the cracks in the S-Z3, S-Z6 and S-Z9 groups were fully repaired by 14 days; in the S-Z12 group, only partial areas of the cracks were filled with precipitates, and the entire crack area was fully repaired when the repair period was extended to 28 days. This may be because, after a prolonged period of reinforcement by the recycled aggregates, the microorganisms embedded in the defective areas were enveloped by precipitates formed through their own mineralization. When the concrete matrix cracked, the number of

microorganisms exposed in the crack area decreased, making effective repair difficult during the early curing process; as the repair period extended, microorganisms from other cracked areas migrated to this location to carry out mineralization and deposition, thereby achieving crack repair [32].

3.5. The Crack Healing Rates of Concrete at Different Repair Times

Figure 7 shows a quantitative analysis of the self-healing performance of concrete cracks after different repair durations. The results indicate that as the repair duration increased, the healing rate of cracks in all experimental groups gradually rose, and the number of fully healed cracks gradually increased. After 28 days of repair, the average healed width and complete closure rate of the cracks in the control group (ordinary recycled concrete) were 0.31 mm and 28%, respectively. In the rapid repair phase (0–7 days, Figure 7a), the crack healing rate in the immobilized mixed-microbial group rose rapidly, approaching 50% by day 7. Cracks with an initial width of 0.3–0.4 mm achieved essentially complete apparent healing, and the maximum reparable crack width reached 0.72 mm. During this phase, the mixed microbial culture was activated by moisture infiltrating the cracks, rapidly metabolizing to produce carbonate ions. These combined with calcium ions to form calcium carbonate precipitates, filling the cracks at a rate far exceeding that of the control group, demonstrating the excellent rapid activation properties of the mixed microbial system. In the slow repair phase (7–14 days, Figure 7b), the healing rate increased from 50% to 70%, and the maximum crack width that could be repaired increased to 1.01 mm. By this stage, most small cracks had been repaired, while the remaining wider cracks continued to be filled slowly. The repair rate slowed down, primarily because residual nutrients were gradually depleted and the metabolic rate of the microorganisms decreased. In the stabilization phase (14–28 days, Figure 7c,d), the healing rate remained largely stable, increasing by only about 10 percentage points, with the maximum reparable crack width reaching 1.26 mm. This indicates that most reparable cracks had been filled, and the system had entered a stable state. The statistical results at 28 days showed that the complete crack repair rate exceeded 60%, with an average repair width of 0.28 mm, meeting the engineering requirements for the self-healing of microcracks in concrete.

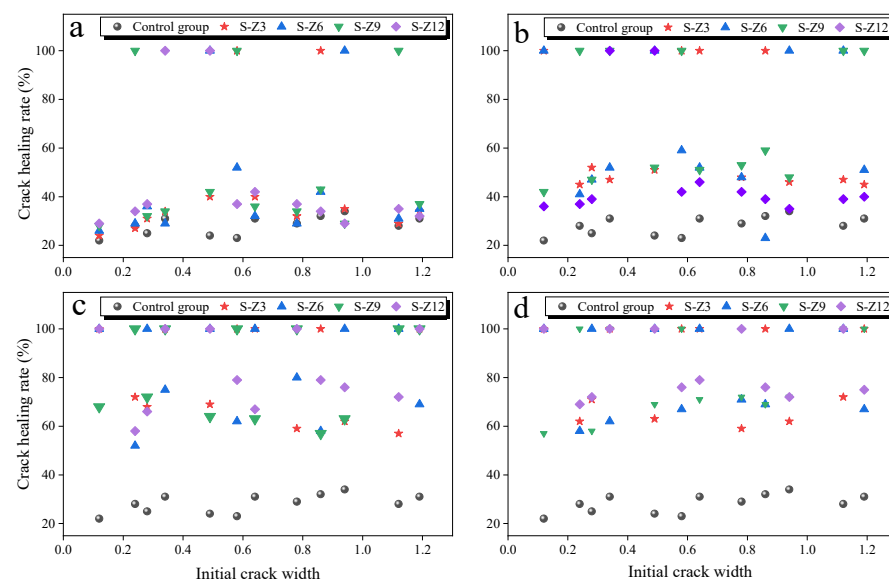


Figure 7. Self-repairing effect of concrete cracks under different repair times: (a), crack healing rate after 7 days; (b), crack healing rate after 14 days; (c), crack healing rate after 21 days; (d), crack healing rate after 28 days.

Compared with the control group, the group without microbial inoculation relied solely on the continued hydration of unhydrated cement in the concrete to achieve self-healing; however, the healing rate was slow and the final healing rate was low, demonstrating that the microbial-loaded system is the key factor in the rapid and efficient repair of cracks [33].

3.6. Analysis of the Compressive Strength of Repaired Concrete

In the control group, which did not undergo the mixed-aggregate fixation treatment, the compressive strength was approximately 35% lower than that of the experimental group shown in Figure 8. The primary reason for this was that the old mortar adhering to the surface of the recycled aggregate contained numerous pores and had low inherent strength. Additionally, the interface transition zone between the aggregate and the new cement paste contained a large number of voids and defects, making it prone to cracking and propagation at the interface under compression, which led to a decrease in overall strength. Compared with the control group, the compressive strengths of the S-Z3, S-Z6, and S-Z9 groups increased by 8.6%, 14.5% and 35.4%, respectively. This indicated that using recycled aggregates enhanced by microbial mineralization as a carrier increased the compressive strength of the self-healing concrete. Biomineralized precipitates filled the voids and defects in the concrete, enhancing its strength and reducing the risk of internal stress concentration. Additionally, mineralization deposits improved the surface properties of recycled aggregates, reduced weak interface zones, and ultimately increased the overall compressive strength of the concrete.

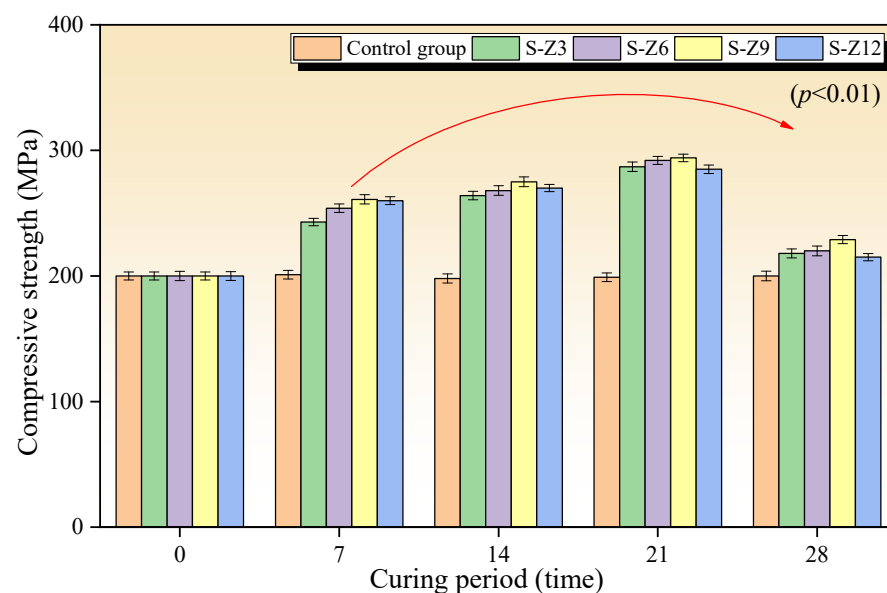


Figure 8. The compressive strength of repaired concrete. $p < 0.01$ indicating that the results have statistical significance.

At the same time, it was evident that the trend in the compressive strength of self-healing concrete aligns with that of the physical and mechanical properties of the recycled aggregates, showing an initial increase followed by a decrease. This phenomenon occurs because, on the one hand, the physical and mechanical properties of the recycled aggregates themselves deteriorated, leading to a decrease in the compressive strength of the recycled concrete; on the other hand, compared to concrete cured for 21 days, the crystals in the surface precipitates of concrete cured for 28 days or longer become loosely arranged and accumulated, forming new voids and cracks. Consequently, the preparation of recycled concrete creates a weak zone at the interface between the recycled aggregates, mineralized

precipitates, and the cementitious matrix, which adversely affects the mechanical properties of the concrete [34,35].

4. Conclusions

This study investigated the use of microorganisms immobilized in enhanced recycled aggregate for repairing concrete. By varying the adsorption and activation times, the study aimed to elucidate the mechanisms underlying the mineralization-enhanced properties of recycled aggregates and the self-healing of concrete cracks.

1. As the duration of mixed-microbial mineralization treatment increased, the water absorption and crushing index of the recycled aggregates first decreased and then increased. After 9 days of mineralization treatment, the water absorption and crushing index of the recycled aggregates showed the greatest reduction, decreasing by 11.4% and 20.4%, respectively.
2. The biomineralized precipitates in concrete cracks were formed by the interlocking of square and rhombohedral crystals, consisting of calcite- and aragonite-type calcium carbonate. The crystals were densely arranged and stacked, and exhibited good compatibility with the cementitious matrix.
3. The optimal adsorption and mineralization times for the recycled aggregate were 15 min and 9 days, respectively. The resulting concrete exhibited a compressive strength 35% higher than that of concrete made with the same recycled aggregate but without reinforcement. The average crack repair width and crack healing rate reached 0.28 mm and 70%, respectively, representing improvements of 39.7% and 42.6% compared to ordinary concrete.

This technology utilized recycled aggregate from construction waste as a microbial carrier, enabling the high-value utilization of construction waste. It addressed the issues of high cost and poor compatibility associated with traditional microbial carriers, offering broad prospects for engineering applications. It can be used on highway pavements, bridge expansion joints, and reinforced beam sections to enable automatic healing of microcracks and enhance structural durability. It can also be applied to dam bodies, impermeable layers, and other areas; after cracks self-heal, the seepage coefficient is reduced, effectively preventing water penetration and erosion, and ensuring the safety of the dam body.

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