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Research Article

Durability of Recycled Concrete after Reinforcing the Aggregates with Permeable Crystalline Materials

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The utilization of recycled aggregate can significantly mitigate the extraction of natural sand and gravel. However, the practical application of recycled aggregate in engineering is impeded by its inherent characteristics, encompassing high water absorption, high crushing, and low apparent density. This study employed a soaking and air-drying method to enhance the strength of three types of aggregates with varying initial strengths by utilizing permeated crystalline materials. The durability of recycled aggregate concrete (RAC) was studied with three different aggregate replacement rates (0%, 50%, and 100%). The test results demonstrate that the slump, compressive strength, freeze resistance, and carbonation resistance of RAC exhibit a decreasing trend as the aggregate replacement rate increases. The freeze resistance and carbonation resistance of RAC are notably enhanced after incorporating permeated crystalline material. This study contributes to a sustainable and efficient solution for the treatment of construction waste, thereby enhancing the utilization rate of recycled concrete.

1. Introduction

The construction industry extensively employs concrete, which is a composite material consisting of cement, coarse aggregate, sand, and water. However, as economic development progresses and infrastructure improvements are made, there is a corresponding surge in the volume of construction waste, which accounts for 6%–10% of global CO_2 emissions. The disposal of demolition and construction waste constitutes a substantial proportion of solid waste, with the majority being deposited in landfills. The investigation of concrete recycled aggregate is therefore of paramount importance in mitigating resource consumption, carbon emissions, waste landfilling, and fostering the sustainable development of future constructions [1]. Waste concrete can be reused as recycled aggregate after proper treatment. However, recycled aggregate concrete (RAC) has some limitations in practical engineering [1, 2]. First, due to the diversity of sources and treatment methods of the recycled aggregate, its mechanical properties are relatively unstable. RAC tends to exhibit poorer mechanical properties and durability compared to natural aggregate concrete (NAC) [3]. Moreover, the water absorption rate of recycled aggregate is higher, and the durability of the concrete made from it is worse, which limits its application in structures requiring long-term use and durability. Additionally, efficient sieving is required to obtain higher quality recycled aggregates, further increasing the production costs of RAC. Therefore, studying and solving the mechanical properties and durability of recycled aggregates is of great practical significance in order to enhance their application value, promote the utilization of recycled materials, reduce environmental impact, and drive engineering practice toward a more sustainable direction.

Scholars have conducted numerous experiments to investigate the properties of recycled aggregates and have found that the higher the replacement rate of recycled concrete aggregate (RCA), the poorer the mechanical properties of RAC [4]. Ashish and Saini [2] and Verma and Ashish [5] compared the properties of continuously recycled coarse aggregate with natural aggregate and found that with an increase in substitution ratio, both plasticity and compressive strength would be reduced. However, continuously recycled coarse aggregate can only be used for low-strength concrete structures. Meanwhile, a study evaluated the effect of density

(a) (b) (c)

Figure 1: Preparation of recycled aggregate: (a) jaw crusher; (b) aggregate after crushing; (c) soaking and strengthening of recycled aggregate.

Table 1: Main chemical composition of ordinary silicate cement.

Material	CaO	SiO_2	Al_2O_3	MgO	SO_3	Fe_2O_3	K_2O	P_2O_5	TiO_2
Content (wt%)	69.32	16.50	3.61	1.24	3.08	4.06	1.28	0.24	0.44

on the compressive strength and ultrasonic pulse speed of geopolymer concrete by replacing normal-weight coarse aggregate with light reclaimed aggregate to achieve a change in density [6]. Zhou and Chen [7] investigated how different types of coarse aggregates affect the mechanical properties of RAC. The test results showed that the type of coarse aggregate has an impact on these properties, with crushed concrete exhibiting lower relative strength and elastic modulus compared to pebble concrete. Wang et al. [8] examined how nanosilica reinforcement affects concrete performance and discovered that both adhesive mortar quantity and original concrete significantly influence RAC durability.

In recent years, numerous studies have claimed that RAC is particularly vulnerable to issues such as chloride erosion, carbonation, freeze–thaw damage, and drying shrinkage. Wu et al. [9] and Bao et al. [3] observed that the chloride ion permeability of RAC increases with the replacement rate of recycled coarse aggregate. Typically, the carbonation depth serves as a measure of the rate at which carbon dioxide penetrates concrete based on its permeability and moisture content [10]. Silva et al. [11] observed that, under identical conditions, the carbonation depth of recycled concrete coarse aggregate can reach 2.5 times that of the corresponding NAC with a probability of 95%. Kazmi et al. [12] studied the freeze–thaw resistance of RCAs by treating them with carbonization, lime carbonization, acetic acid impregnation, friction and acetic acid impregnation, and acetic acid impregnation and carbonization. The results show that the treated RCA exhibits better performance in frost melting resistance and sulfate resistance. Nobre et al. [13] investigated the substitution rate and shrinkage rate of RCA. Their findings indicated that the shrinkage rate of RAC follows a logarithmic pattern with time, with most shrinkage occurring early on and stabilizing later. Furthermore, some researchers have shown that incorporating nanomaterials into RAC enhances concrete performance [14, 15], resulting in improved mechanical properties and durability of the concrete [16]. Ashish and Verma [17] demonstrated the potential to replace natural aggregate (NCA) in concrete manufacturing by using continuous RCA (SRCA). They evaluated the mechanical and permeable properties by adding 10% silica ash (SF) to the replacement ratio ranging from 0% to 100%. The results showed that, in the presence of 10% SF, replacing NCA with SRCA can achieve improved results at a 25% replacement ratio while partially offsetting the loss of permeability. Sharma et al. [18] proposed an ideal biological method to effectively improve the performance of recycled aggregates. Additionally, they developed low-carbon RAC through carbonization treatment and Alccofine technology, making substantial contributions to reducing carbon footprint and improving concrete sustainability [19].

In summary, although previous studies have revealed the problems of mechanical instability, compressive strength decline, durability challenges, and production costs of RAC, few methods have been proposed to enhance the performance of recycled aggregate. This study explores in depth the effects of specific factors, such as initial strength, replacement rate, and reinforcement with permeable crystalline materials on durability. The permeable crystalline materials used in this study can significantly improve the durability of RAC. At the same time, compared with nanorepair technology and biological methods that have been studied, permeable crystal materials also possess a certain degree of self-healing and repair ability. By expanding the scope of applications for recycled aggregates in practical engineering projects, this research is expected to contribute to sustainable building practices and fill knowledge gaps regarding interrelationships among factors affecting RAC performance.

2. Materials and Methods

2.1. Materials

2.1.1. Concrete Materials. The raw materials used in this paper include cement, sand, coarse aggregate, water reducer, and water are shown in Figure 1. The cement used is PO · 42.5 ordinary Portland cement with a density of 3.21 g/cm^3. Its main components were detected by an X-ray fluorescence spectrometer, as shown in Table 1. The size of natural river sand ranges from 0.075 to 4.75 mm, with an apparent density of 2.64 g/cm^3 and a fineness modulus of 2.6. The results of

Table 2: Sieve analysis results of natural river sand.

Group	1	2	3	4	5	6	7
Screen size (mm)	4.75	2.36	1.18	0.6	0.3	0.15	0.075
Weight of screen residue (g)	0.00	67.20	101.50	86.10	93.20	118.90	30.10
Divide the screening rate (%)	0.00	13.44	20.30	17.22	18.64	23.78	6.02
Cumulative screening rate (%)	0.00	13.75	34.16	51.39	70.05	93.68	100
Fineness modulus	$2.3 < M_x = 2.6 < 3.0$ (medium sand)						

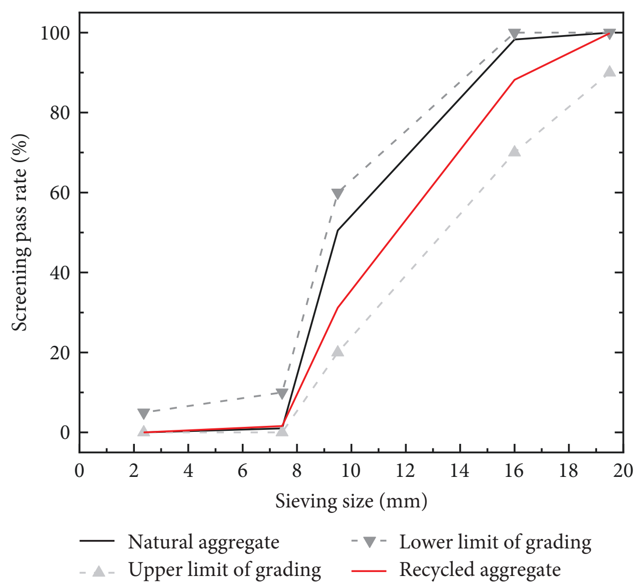


Figure 2: Recycled aggregate screening curve.

Table 3: Recycled aggregate concrete proportion design.

Group	Specimen number	Concrete component (kg/m³)						
		C	W	S	NA	RA	CRA	SP
1	NAC	380	195	630	1,188	—	—	0.93
2	CAR30-100	380	195	630	—	—	1,188	0.93
3	CRA30-50	380	195	630	594	—	594	0.93
4	CRA20-100	380	195	630	—	—	1,188	0.93
5	CRA20-50	380	195	630	594	—	594	0.93
6	CRA10-100	380	195	630	—	—	1,188	0.93
7	CRA10-50	380	195	630	594	—	594	0.93
8	RA30-100	380	195	630	—	1,188	—	0.93
9	RA30-50	380	195	630	594	594	—	0.93
10	RA20-100	380	195	630	—	1,188	—	0.93
11	RA20-50	380	195	630	594	594	—	0.93
12	RA10-100	380	195	630	—	1,188	—	0.93
13	RA10-50	380	195	630	594	594	—	0.93

the screening analysis are shown in Table 2. For coarse aggregate, natural sizes of 5–10 and 10–20 mm, as well as recycled aggregates prepared from three different initial strengths of concrete (C10, C20, and C30), are selected. The mass ratio between large aggregates and small aggregates is 4 : 6. The screening curve is shown in Figure 2.

2.1.2. Permeate Crystalline Materials. In this paper, the permeable crystal materials developed by Suzhou Jiagushi New Material Technology Co., Ltd. are selected. Compared with traditional materials, permeable crystalline materials are more environmentally friendly and efficient. The "nano-grade" silicate in the permeable crystalline materials can chemically react with the calcium ions in the old mortar to make the structure of the aggregate denser, while inhibiting the intrusion of deterioration factors such as carbonate gas and water, thus improving the strength and quality of concrete. The reinforced slurry penetrant crystal strengthening solution is primarily composed of sodium silicate, supplemented by three auxiliary components. The inclusion of sodium borate and sodium silicate aligns with the glass structure and regulates the strength of the solidified crystals. Sodium hexametaphosphate facilitates water softening treatment by complexing calcium and magnesium ions present in hard water. Polycarboxylic acids reduce interfacial tension, lower the viscosity of the strengthened slurry, and enhance its fluidity. To prepare this solution, a 15% concentration sodium silicate solution is initially prepared through heating and stirring. Subsequently, different additives are weighed based on their mass percentage relative to the solid form of sodium silicate, added to the prepared sodium silicate solution, and finally heated and stirred until complete dissolution occurs to yield a strengthened slurry.

2.2. Experimental Design. The water absorption rate of recycled aggregate is still much higher than that of natural aggregate. The water absorption rate has a certain influence on the slump, mechanical properties, and durability of aggregate. To mitigate the impact of water absorption rate on recycled aggregate, it is necessary to carry out water filling treatment during concrete mixing. Weigh the recycled aggregate according to the ratio, soak it in water for 1 hr, and remove any surface water before use. Then, pour the recycled aggregate, natural aggregate, sand, and cement into the mixer for 30 s. Afterward, add in the water and water-reducing agent for 3 min before transferring it into a prepared mold and placing it on a shaking table to vibrate and compact. Once cured, remove the mold and label each specimen with a number.

2.3. Mix Ratio. The water–cement ratio of RAC is 0.51, the sand rate is 35%, and the amount of water-reducing agent is 2.4% of the cement quantity. The cement quantity used is 380 kg/m³, and the water consumption is 195 kg/m³. The ratio between coarse and fine aggregates is $m_{5-10} : m_{10-20} = 4 : 6$, as shown in Table 3.

Table 4: The specific uses and dimensions.

Project	Sample size	Number of sample groups	Total	Remark
7-Day compressive strength	100 mm × 100 mm × 100 mm	13	39	All test three specimens in a group
28-Day compressive strength	100 mm × 100 mm × 100 mm	13	39	
Carbonizing test	100 mm × 100 mm × 100 mm	13	117	
Freeze–thaw test	400 mm × 100 mm × 100 mm	13	39	

Figure 3: Compressive test of concrete.

Figure 4: Carbonation test of recycled aggregate concrete.

2.4. Specimen Design. Mechanical property tests and durability tests are designed according to the specifications. The specific uses and dimensions are shown in Table 4.

2.5. Test Methods

2.5.1. Slump of RAC. Dampen and clean the inner and outer walls of the bottom plate and slump bucket using a moist cloth, then securely position the funnel on top of the slump bucket. Divide the on-site mixed RAC into three layers, depositing them successively into the slump bucket. Use a vibratory rod to vibrate and level each layer accordingly. After completion, remove any excess concrete from the top surface. Cleanse residual concrete around the edge of the slump bucket before lifting it steadily in a vertical manner, ensuring completion within 5–10 s. Gradually raise the collapsible drum while measuring its height until reaching its apex after collapsing.

2.5.2. Mechanical Properties of RAC. The mechanical properties test of RAC is shown in Figure 3. After removing the specimen from the curing box, the test is promptly conducted to measure whether the size of the specimen meets the standards. Then, place the specimen on the center of the bottom pressure plate of the test machine and adjust both compressive strength coefficient and loading speed are adjusted according to the design strength and size of the concrete. During testing, a loading speed of 0.5 MPa/s was used with a coefficient of 0.95. Three specimens were measured in each group, and their arithmetic mean value was taken as the compressive strength. Therefore, the compressive strength of concrete can be expressed as follows:

$$f_{cu,k} = 0.95 \times \frac{F}{A}. \quad (1)$$

In Equation (1), $f_{cu,k}$ is the compressive strength of concrete cube (MPa), F is the specimen breaking peak value (N), A is the bearing area of specimen (mm^2).

2.5.3. Carbonation Test of RAC. The carbonation test of RAC is shown in Figure 4. After curing for 28 days in the standard curing box, remove the concrete test block and place it in an oven at 60°C for 48 hr to dry. Once dried, seal the remaining concrete surfaces with epoxy resin and draw parallel lines with a spacing 10 mm on the exposed sides. Place the treated specimen on a bracket in the carbonization box, ensuring that there is no less than a 50 mm spacing. The dioxygen concentration in the carbonization chamber is maintained at $20\% \pm 3\%$, while the humidity and temperature are controlled at $70\% \pm 5\%$ and 20 ± 2°C, respectively. Upon completion of the carbonation period, carefully extract the specimens from the chamber and employ a cutting machine to prepare concrete test blocks for subsequent titration with a phenolphthalein alcohol solution (1%). It is crucial to ensure that the measurement accuracy of carbonation depth for each section falls within ±0.5 mm. The evaluation carbonization depth can be expressed as follows:

$$\overline{d}_t = \frac{1}{n}\sum_{i=1}^{n} d_i. \quad (2)$$

In Equation (2), $\overline{d}_t$ is the evaluation carbonization depth of specimens after t days of carbonization (mm), d_i is the carbonization depth of each measuring point, n is the total number of measuring points.

2.5.4. Freeze–Thaw Cycle Test of RAC. The freeze–thaw cycle test of RAC is shown in Figure 5. After being cured for 24 days, the specimen should be removed from the curing

Figure 5: Freeze–thaw cycle test of recycled aggregate concrete.

box and immersed in water at a temperature of $20 \pm 2°C$ for 4 days. Submerge the specimen in water, wipe off any surface moisture with a damp cloth to assess its appearance, and proceed with weighing and measuring its elasticity modulus. Quality measurements and appearance photography are conducted in 25 freezing cycles. If the average mass loss rate of specimens in a group exceeds 5%, the freezing and thawing cycle test will be discontinued. The mass loss rate can be expressed as follows:

$$\Delta W_{ni} = \frac{W_{0i} - W_{ni}}{W_{0i}} \times 100, \tag{3}$$

$$\Delta W_n = \frac{\sum_{i=1}^{3} \Delta W_{ni}}{3} \times 100. \tag{4}$$

In Equations (3) and (4), ΔW_{ni} is the mass loss rate (%) of the i specimen after N freeze–thaw cycles, W_{0i} is the mass of the ith concrete specimen before freeze–thaw cycle test (g), W_{ni} is the mass of the ith specimen after N freeze–thaw cycles (g), ΔW_n The average mass loss rate (%) of a group of concrete specimens after N freeze–thaw cycles.

3. Results and Discussions

3.1. Slump of the RAC. In the experimental design, natural aggregates were replaced with 0%, 50%, and 100% recycled aggregates. The recycled aggregates were soaked and air-dried for a total of 28 days. It can be observed from Figure 6 that the slump of NAC is 180 mm. When the aggregate replacement rate is 50%, the slumps of the three kinds of RAC are 130, 110, and 110 mm, respectively. When the replacement rate of RAC is 100%, the slump of three types of RAC is 120, 100, and 90 mm, respectively. As the replacement rate of recycled aggregate increases from 0% to 50%, the slump of the types of RAC decreases by 50, 70, and 70 mm, respectively. When the replacement rate of recycled aggregate reaches 100%, the slump of the three kinds of RAC decreases by only 10, 10, and 20 mm, respectively. The comprehensive analysis indicates that the slump of RAC decreases as the replacement rate of recycled aggregate increases. The reasons are as follows: first, a substantial amount of old mortar adheres to the surface of aggregate, leading to an increase in needle flake content in RAC. This roughened surface enhances interaggregate friction. Second, as the proportion of recycled aggregate increases, some mixed water is absorbed by the concrete aggregates, leading to a reduction in the effective water–cement ratio.

When the replacement rate is 50%, the slump of RAC after strengthening is 160, 150, and 130 mm, respectively. When the replacement rate is 100%, the slump of strengthened RAC increases to 140, 130, and 100 mm, respectively. Consequently, it is evident that the slump of strengthened RAC exhibits an increase of 20, 20, and 30 mm, respectively. Through comprehensive analysis, it has been demonstrated that the incorporation of permeable crystalline materials has resulted in a significant enhancement of the slump performance of RAC. The analysis reveals that the water absorption rate of reinforced recycled aggregate has decreased. Consequently, this results in an elevated effective water–cement ratio and subsequently enhances the slump of reinforced RAC.

3.2. Mechanical Properties of RAC. In this study, the water–cement ratio of NAC is 0.51, while recycled aggregates were used to replace 0%, 50%, and 100% of the original aggregates. The impact of strengthening with permeable crystalline materials on the mechanical properties of recycled aggregate was investigated, and the results are presented in Figure 7.

As shown in Figure 7, the 7-day compressive strength of NAC is 30.7 MPa, and the 28-day compressive strength is 40.0 MPa, which is higher than that of the three types of RAC. When the aggregate replacement rate is 50%, the 7-day compressive strength of the three types of RAC is lower than that of NAC by 10.30%, 20.17%, and 32.65%, respectively. While the corresponding reduction in the 28-day compressive strength is by 7.92%, 18.21%, and 27.69%. When the aggregate replacement rate is 100%, the 7-day compressive strength of the RAC is lower than that of NAC by 20.93%, 31.34%, and 37.20%, respectively, and the 28-day compressive strength is lower than that of NAC by 12.68%, 97%, and 32.94%, respectively. The experimental results demonstrate that the compressive strength of RAC exhibits a decline as the replacement rate of aggregate increases, and this decline is further exacerbated by the lower initial strength of recycled aggregates. The surface of recycled aggregate contains a significant amount of old mortar, which contributes to an increase in the interface transition zone of RAC and subsequently decreases its overall strength. Additionally, the strength of the aggregate also affects the performance of RAC and a reduction in their strength results in a corresponding decrease in the compressive strength of concrete.

Figure 7 shows that as the rate of recycled aggregate in concrete increases by 50%, the compressive strength of RAC strengthened by permeable crystalline materials increases by 11.70%, 17.55%, and 20.29% for the 7-day compressive strength, and by 17.17%, 5.50%, and 7.61% for the 28-day compressive strength, respectively. Furthermore, when the replacement rate of RAC reaches 100%, the use of permeable crystalline materials also improves its compressive strength, with a respective increase in the 7-day compressive strength

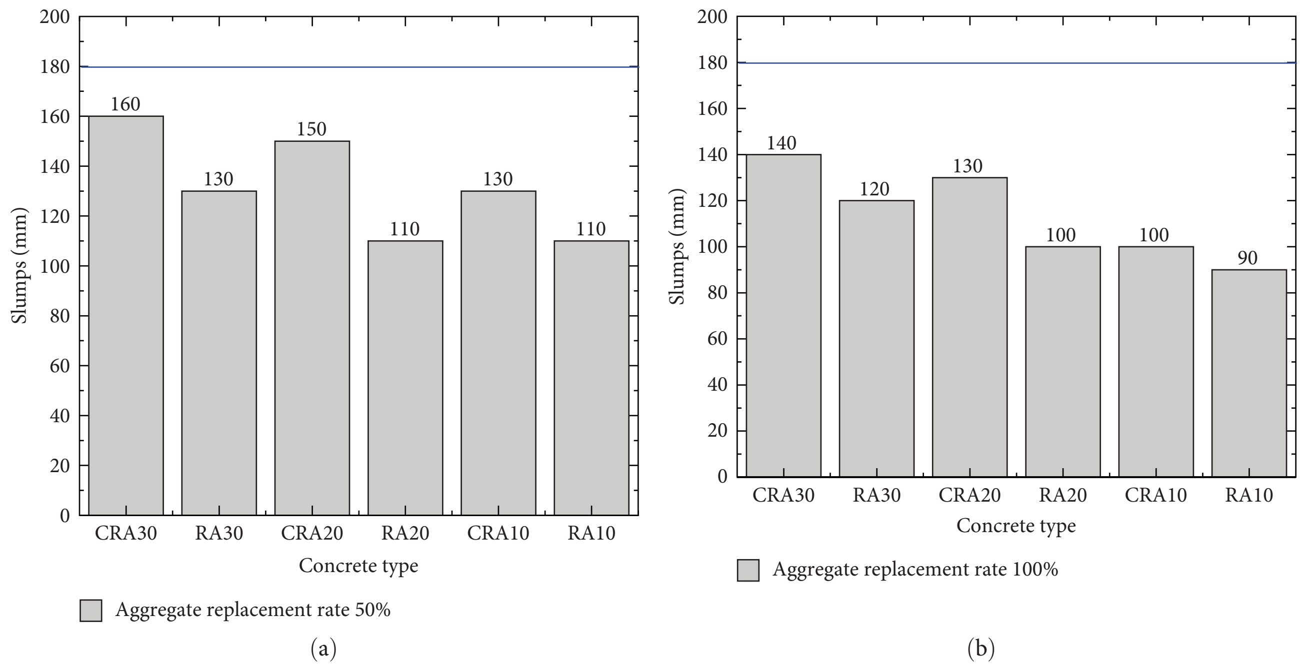


Figure 6: Slump of the recycled aggregate concrete: (a) 50% replacement rate; (b) 100% replacement rate.

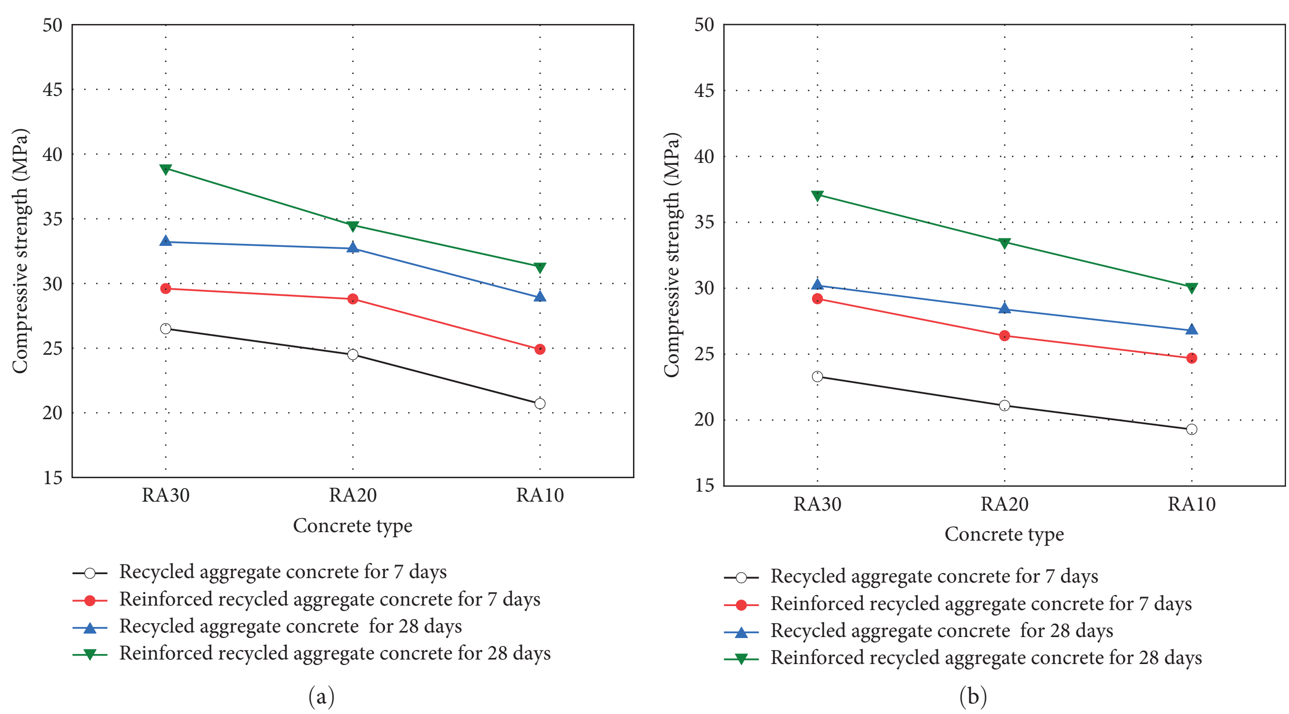
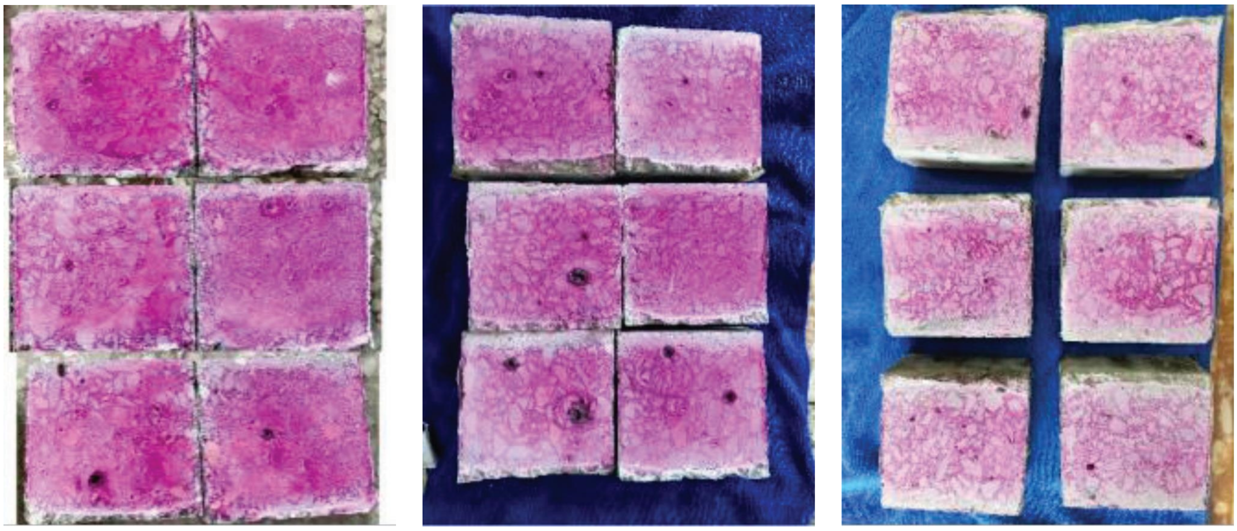


Figure 7: Compressive strength of recycled aggregate concrete: (a) 50% replacement rate; (b) 100% replacement rate.

by 25.32%, 25.12%, and 27.98%, and an increase in the 28-day compressive strength by 15.58%, 17.96%, and 12.31%, respectively.

The 7- and 28-day compressive strength of RAC, with different substitution rates and initial strength, improves after being reinforced by permeable crystalline material. The analysis shows that, after soaking in the permeable crystalline material, the nanosilicon ions react with the calcium ions in the mortar within the recycled aggregate.

As a result, the generated crystalline material fills some of the pores and cracks, while the unreacted silicate will directly fill the remaining pores and cracks in the old mortar, making it denser. Numerous unreacted silicate crystals are attached to the surface of the recycled aggregate after being strengthened



(a) (b) (c)

FIGURE 8: Depth of carbonation of natural aggregate concrete: (a) 7 days; (b) 14 days; (c) 28 days.

(a) (b) (c)

FIGURE 9: Depth of carbonation of CRA30 recycled aggregate concrete: (a) 7 days; (b) 14 days; (c) 28 days.

by penetrating crystalline materials. During the process of mixing concrete, these crystals disperse into the concrete matrix, promoting cement hydration reaction and improving both mortar strength and microstructure of newly mixed concrete. Consequently, this enhances the performance of RAC. The unreacted nanosilicon ions on the surface of the aggregate are simultaneously incorporated into the concrete matrix material, thereby enhancing the hydration reaction of the cement. As a result, the compressive strength of reinforced RAC is improved. The increase in compressive strength for concrete with a 100% aggregate replacement rate strengthened by permeable crystalline material is greater than that for concrete with a 50% replacement rate. According to the analysis, when the aggregate substitution rate is 100%, more nanosilicon ions attach to the aggregate surface after permeable crystallization materials are dispersed into the concrete matrix during the mixing process. These ions undergo a secondary hydration reaction with cement, greatly improving the strength and microstructure of mortar, resulting in a significant increase in the compressive strength of concrete. Therefore, the reinforcement of penetrable crystals improves the compressive strength of RAC.

3.3. Carbonization Performance of RAC. The morphology of three types of concrete specimens after carbonization is depicted in Figures 8–10. It can be observed from the figures that, for the same duration of carbonation, the order of carbonation depth for these three types of concrete is

(a) (b) (c)

Figure 10: Depth of carbonation of RA30 recycled aggregate concrete: (a) 7 days; (b) 14 days; (c) 28 days.

Table 5: Depth of carbonation of recycled aggregate concrete.

Aggregate type	Recycled aggregate substitution rate (%)	Carbonation depth (mm)		
		7 days	14 days	28 days
NA	0	2.45	5.21	11.25
RA10	50	8.12	13.23	20.50
RA10	100	9.32	16.12	23.56
CRA10	50	6.36	11.35	18.64
CRA10	100	7.55	12.52	20.14
RA20	50	5.12	10.34	19.31
RA20	100	7.16	12.15	21.26
CRA20	50	4.22	7.53	14.54
CRA20	100	5.14	8.58	17.47
RA30	50	4.56	8.41	17.53
RA30	100	6.36	10.51	19.58
CRA30	50	3.49	7.23	13.36
CRA30	100	5.36	8.12	16.13

NAC < CRAC < RAC. Additionally, as time increases, the difference in carbonation depth becomes more pronounced.

The carbonization depth of RAC was assessed using phenolphthalein solution at 7, 14, and 28 days before and after reinforcement. The corresponding results are presented in Table 5. It can be observed from the test data that an increase in carbonization time leads to a proportional increase in the depth of carbonization. Additionally, with an increase in the replacement rate of recycled aggregate with the same initial strength, the depth of carbonization also intensifies. Furthermore, for a constant replacement rate of recycled aggregate, a decrease in the initial strength of regenerated aggregate results in a deeper carbonization depth.

Figures 11–13 depict the relationship between carbonization depth and time for three types of RAC with different initial strengths after being reinforced by permeable crystalline materials. From the aforementioned figures, it can be observed that when the replacement rate of recycled aggregate is 50%, the 7-day carbonization depth of these RAC strengthened by osmotic crystalline materials decreases by 21.67%, 17.58%, and 23.46%, respectively. While the corresponding reductions in carbonization depth on Day 14 are 14.21%, 27.18%, and 14.03%. Finally, on Day 28, there is a decrease of 9.07%, 24.70%, and 23.79%. When the replacement rate of recycled aggregate is 100%, the 7-day carbonization depth of the three types of RAC strengthened by permeable crystalline materials decreases by 18.99%, 28.21%, and 15.72%. Additionally, the 14-day carbonization depth decreases by 22.33%, 29.38%, and 22.74%. Furthermore, the reduction in carbonation depth on Day 28 is observed to be around 14.52%, 17.83%, and 17.62%. These results indicate that for concrete with different initial strengths and aggregate replacement rates, permeable crystallization can improve the carbonization resistance of recycled aggregates.

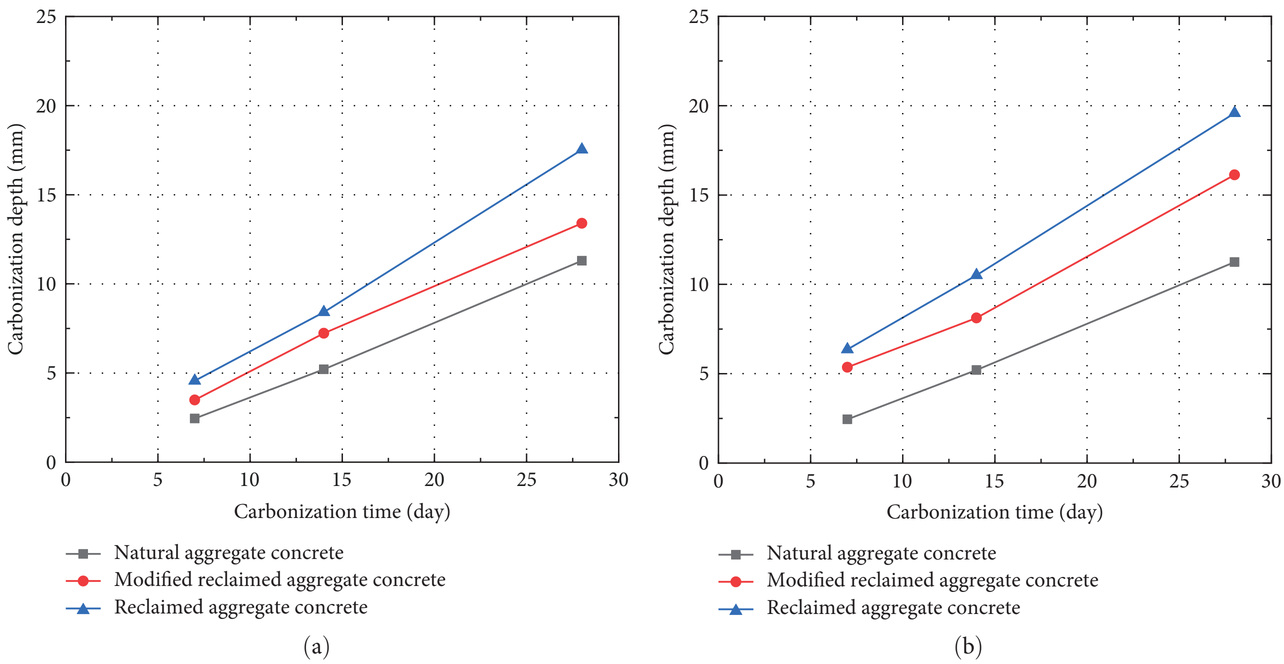


Figure 11: Depth of carbonation of RA30 concrete: (a) 50% replacement rate; (b) 100% replacement rate.

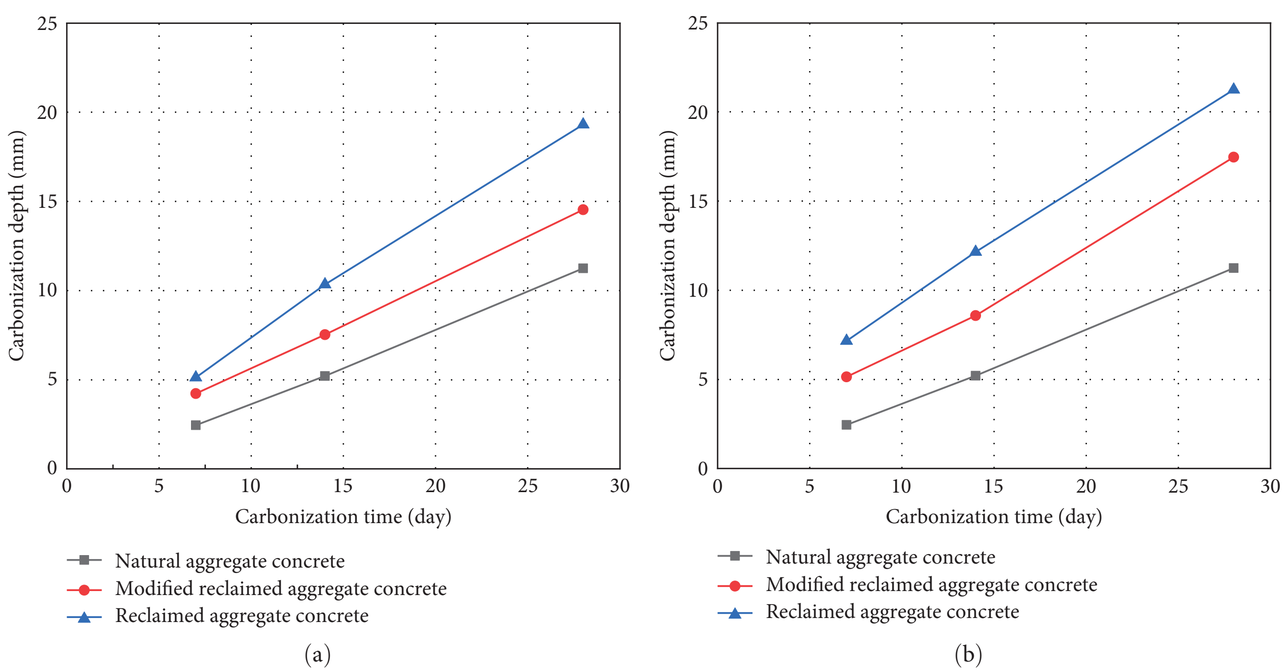


Figure 12: Depth of carbonation of RA20 concrete: (a) 50% replacement rate; (b) 100% replacement rate.

The principle of carbonization in concrete is that under the condition of biochemical interaction with water, carbon dioxide, and calcium hydroxide react to form calcium carbonate and water, causing the loss of alkali in concrete. During the preparation process of recycled aggregate, additional microcracks are caused, which result in more water absorption during mixing as the content of recycled aggregate increases. Consequently, an increase in pores and cracks during concrete carbonization leads to deeper diffusion channels and a greater depth of carbonization. The higher the replacement rate, the poorer its carbonation performance.

The water absorption of three types of reinforced recycled aggregate with different initial strengths decreased after being strengthened by the permeation of crystalline material. The crystalline material mainly contains silicate ions with the strong calcium oxide from the old mortar, which forms

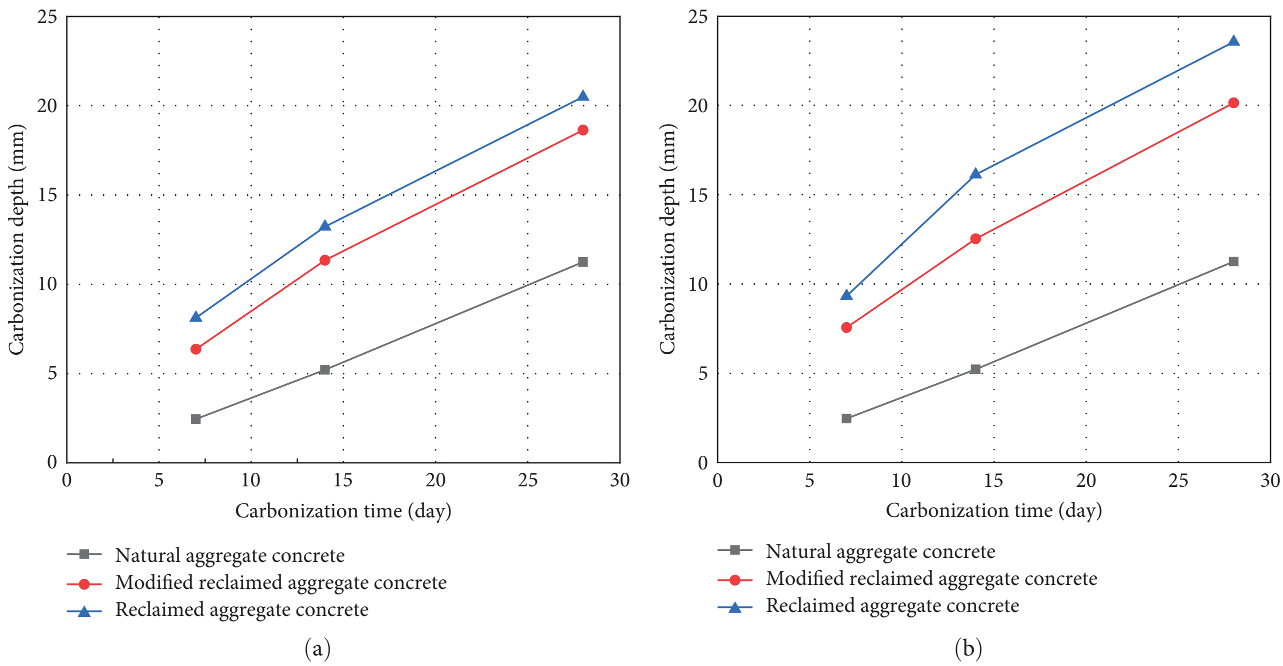


FIGURE 13: Depth of carbonation of RA10 concrete: (a) 50% replacement rate; (b) 100% replacement rate.

(a) (b) (c)

FIGURE 14: Freeze–thaw phenomenon of natural aggregate concrete: (a) 50 times; (b) 100 times; (c) 150 times.

C–S–H crystals and consumes the content of CH substance in the mortar. The C–S–H crystals fill some pores and cracks, making the internal structure of RAC denser. Due to their small particle size, incomplete nanosilicon ions directly fill some larger pores and cracks, resulting in a filling effect. The diffusion channel for carbon dioxide in RAC is reduced when strengthened by osmotic crystal material, leading to a decrease in the water absorption rate for recycled aggregate and an improvement in its carbonization performance.

The rate of carbonization depth growth in concrete decreases as the duration of carbonization increases. This phenomenon has also been observed in [20]. This is due to the formation of calcium carbonate, which blocks certain pores and cracks, resulting in a reduction in diffusion channels for carbon. Consequently, the rate of carbonization depth growth in RAC also decreases with longer durations of carbonization.

3.4. Frost Resistance of RAC. According to the test plan, the test block was removed 25 times per freeze–thaw for quality testing and surface morphology observation. As depicted in Figures 14–16, after 50 freeze–thaw cycles, mortar falls off from the surfaces of the concrete, with the unreinforced RAC experiencing the most severe damage. After 100 freeze–thaw cycles, all three groups of concrete test blocks exhibit a more significant detachment of mortar and fine aggregates. The unreinforced RAC test block displays small holes and defects at corners. The permeable crystalline material-strengthened aggregate concrete test block exhibits an area of particles falling off, but overall damage is less severe compared to that observed in unreinforced concrete test blocks. After 150 freeze–thaw cycles, a substantial amount of coarse aggregates is exposed on the surface of the unreinforced RAC test block, along with instances of detachment of coarse aggregate. In contrast, while both permeable crystalline material-

(a) (b) (c)

Figure 15: Freeze–thaw phenomenon of CRA30 recycled aggregate concrete: (a) 50 times; (b) 100 times; (c) 150 times.

(a) (b) (c)

Figure 16: Freeze–thaw phenomenon of RA30 recycled aggregate concrete: (a) 50 times; (b) 100 times; (c) 150 times.

Table 6: Recycled aggregate concrete freeze–thaw mass loss results.

Aggregate type	Recycled aggregate substitution rate (%)	Quality loss rate (%)								
		0	25	50	75	100	125	150	175	200
NA	—	0	−0.20	0.18	0.54	1.17	1.51	2.31	2.98	3.68
RA10	50	0	−0.63	0.56	1.25	1.67	2.33	3.65	4.59	5.32
RA10	100	0	−0.78	0.62	1.36	1.98	2.68	3.79	4.89	5.64
CRA10	50	0	−0.37	0.29	1.09	1.45	1.98	3.11	3.68	4.13
CRA10	100	0	−0.55	0.32	1.12	1.68	2.34	3.36	4.12	4.89
RA20	50	0	−0.52	0.50	0.93	1.50	2.31	3.43	3.97	4.59
RA20	100	0	−0.61	0.46	1.02	1.66	2.42	3.56	4.11	4.87
CRA20	50	0	−0.38	0.46	0.81	1.36	2.09	3.03	3.45	4.11
CRA20	100	0	−0.41	0.35	0.89	1.89	2.23	3.32	3.68	4.36
RA30	50	0	−0.37	0.27	0.88	1.36	2.12	2.93	3.45	4.12
RA30	100	0	−0.54	0.39	0.93	1.55	2.64	3.35	3.87	4.35
CRA30	50	0	−0.31	0.28	0.62	1.25	1.70	2.61	3.23	3.98
CRA30	100	0	−0.49	0.57	0.73	1.78	2.03	3.12	3.56	4.08

strengthened RAC and NAC test blocks exhibit extensive mortar shedding, no coarse aggregates detach. Therefore, NAC experiences widespread loss of mortar but maintains a relatively intact bond between aggregates.

The data in Table 6 demonstrates the rate of quality deterioration in RAC after undergoing a freeze–thaw cycle. Following the freeze–thaw cycle test, the quality of NAC, reinforced RAC, and unreinforced RAC all experienced varying degrees of decline. After 25 freeze–thaw cycles, there was a slight improvement in the quality of all concretes. This can be attributed to water absorption expansion and increased ice volume during saturation, resulting in more cracks. Consequently, when the temperature rises, more water enters the concrete, leading to a minor improvement in its quality.

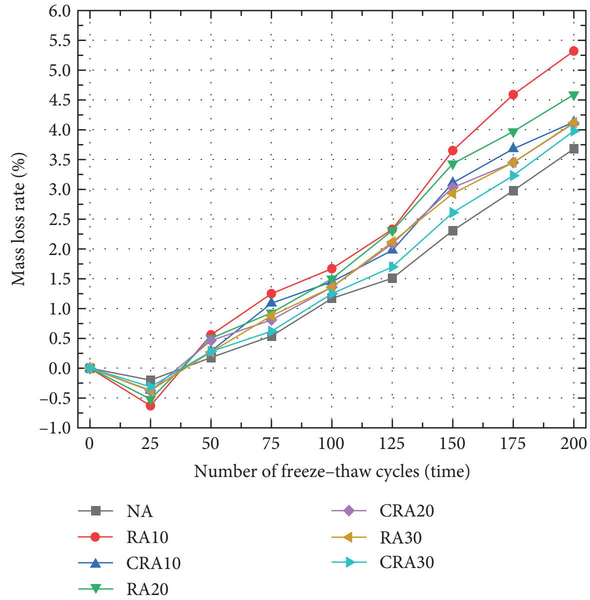


FIGURE 17: Aggregate replacement rate 50% recycled aggregate concrete freeze–thaw results.

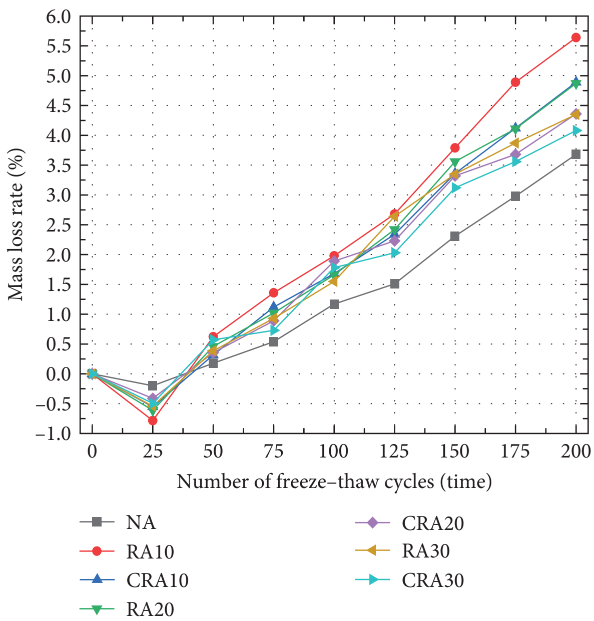


FIGURE 18: Aggregate replacement rate 100% recycled aggregate concrete freeze–thaw results.

However, after 50 freeze–thaw, there is a gradual decrease in the quality of RAC due to the continuous expansion of frozen within cracks, causing internal structural damage and surface spalling on the concrete specimen. As a result, the overall quality continuously decreases.

Figures 17 and 18 depict the freeze–thaw quality loss rate of RAC before and after reinforcement, with aggregate replacement rates of 50% and 100%, respectively. After undergoing 50 freeze–thaw cycles, the maximum rate for RAC with a 100% replacement rate is 0.62%, which is 0.06% lower than that of the concrete test block with a 50% replacement rate. Following 75 freeze–thaw cycles, the maximum mass loss rate for RAC with a full replacement rate reaches up to 1.36%, which is also lower by approximately 0.11% compared to the concrete test block containing a half replacement rate. The quality loss rate due to freeze–thaw cycling increases as the percentage of replaced aggregates rises. Upon analysis, this can be attributed to both the high content of needlelike particles in recycled aggregates themselves and the significant presence of old mortar within them. Consequently, as more aggregates are replaced in RAC, its structural density freezable water content increases, leading to reduced frost resistance.

With the same aggregate substitution rate, the effect of reinforced recycled aggregate by permeating crystalline material on the frost resistance of RAC was analyzed. When the aggregate replacement rate was 50% and the number of freeze–thaw cycles was 100 times, the mass loss rates of reinforced RAC were 1.45%, 1.36%, and 1.25%, respectively. The unreinforced RAC had mass loss rates of 1.67%, 1.50%, and 1.25% under the same conditions, respectively. When the number of freeze–thaw cycles increased to 200 times, the quality loss rates for reinforced RAC were measured at 4.13%, 4.11%, and 3.98%. In comparison, unstrengthened RAC showed quality loss rates of 5.32%, 4.59%, and 4.12%. The same trend was observed when using a complete replacement rate (100%) for aggregates. An analysis revealed that after modifying with permeating crystalline material, sodium silicate in this material reacted with old mortar to form more C–S–H crystals, which filled internal cracks and pores, reducing water absorption rate in regenerated aggregates while improving their performance and decreasing porosity. The same phenomenon is also observed in [21]. Nano-Tio_2 has a remarkable modification effect on reclaimed aggregate concrete. Nano-Tio_2 can reduce the cumulative water absorption and porosity of RAC and alleviate the negative influence of recycled coarse aggregate on the capillary water absorption of concrete after freeze–thaw cycle. Through scanning electron microscope observation, a large amount of C–S–H gel was produced in the concrete doped with nano-Tio_2, which bonded the pores and cracks in the concrete together to form a dense structure. Additionally, during the concrete preparation process, more silicate dispersed into the internal structure promoted cement hydration reaction, leading to improved density as well as strength in the transition interface zone, thus enhancing frost resistance in concrete. After an equal number of freeze–thaw cycles, reinforced RAC exhibited lower quality loss rates compared to other samples tested.

4. Conclusion

In this paper, the aggregates of RAC were reinforced with a permeable crystalline material. The replacement rate of recycled aggregate was designed to be 0%, 50%, and 100%. Slump, mechanical properties, and durability of the RAC before and after reinforcement were studied. It was found that the performance of RAC improved when it was strengthened by osmotic crystalline material. The primary conclusions from this study are as follows:

(1) The slump of permeable crystalline material-strengthened RAC is enhanced. This can be attributed to the reduced water absorption rate of reinforced recycled aggregate, resulting in lower water absorption and an increased effective water–cement ratio, ultimately leading to an increase in the slump of reinforced RAC.
(2) When the aggregates are reinforced with permeable crystalline material, the compressive strength of RAC significantly improves at both 7- and 28-day intervals for various replacement rates and initial strengths. For instance, at a replacement rate of 50%, the compressive strength increases by 11.70%, 17.55%, and 20.29% after 7 days, while it increases by respective values of 17.17%, 5.50%, and 7.61% after 28 days compared to regular concrete without reinforcement from permeable crystalline materials.
(3) Under varying initial strengths and different rates of aggregate replacement, the incorporation of permeable crystalline material can effectively enhance the carbonization resistance of regenerated aggregates. This enhancement can be attributed to a reduction in carbon dioxide diffusion pathways within RAC reinforced by permeable crystalline materials.
(4) The quality deterioration in the freeze–thaw cycle of RAC increases with an increase in the replacement rate of aggregates. When considering the same aggregate replacement rate, reinforced RAC exhibits a lower rate of quality deterioration compared to unreinforced RAC after undergoing various freeze–thaw cycles.

The permeable crystallization material has been demonstrated as an effective approach to enhance the performance of RAC in this study. However, further investigation is required to compare different reinforcement methods and determine the optimal manners and dosage of osmotic crystallization material.

Data Availability

The data are not publicly available due to privacy.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

Methodology, writing-original draft, and supervision were done by J.L.; conceptualization and investigation were done by F.L.; software-related task and investigation were done by J.G.; methodology and investigation were done by L.Z; data curation, writing—original draft, and supervision were done by X.T.; and project administration was done by X.L.

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