

Article

Numerical Simulation and Experimental Validation of the Resistance of Recycled Aggregate Concrete to Chloride Penetration Under Freeze-Thaw Cycles

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Abstract

This study investigated the resistance of recycled aggregate concrete (RAC) to chloride penetration under freeze-thaw cycles using both numerical simulation and experimental validation. A five-phase mesoscale model of RAC was developed. The salt freeze-thaw test was conducted to validate the simulated values and explore the effects of different recycled coarse aggregate (RCA) substitution ratios, as well as varying dosages of fly ash and superfine fly ash, on chloride concentration in RAC. The experimental data showed satisfactory agreement with the simulated values, confirming the model's validity. Additionally, the RCA volume fraction, interfacial transition zone (ITZ) thickness, and adhesive ratio of old mortar were analyzed using simulation. The variation patterns of compressive strength, relative dynamic elastic modulus, and mass loss of RAC also revealed the mechanisms by which RCA substitution ratio and the dosages of fly ash and superfine fly ash act under salt freeze-thaw conditions. This study provides guidance for enhancing the resistance of RAC to chloride penetration and its durability under freeze-thaw conditions.

Keywords: recycled aggregate concrete; chloride penetration; freeze-thaw cycles; numerical simulation; experimental validation



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1. Introduction

In recent years, the urbanization process has led to a significant increase in construction and demolition waste (C&DW). Finding ways to reuse C&DW has become an urgent issue that needs to be addressed [1–3]. Recycled concrete technology maximizes the potential of C&DW by using it as recycled aggregates, providing partial or complete substitutes for natural aggregates in pouring new concrete [4,5]. Recycled aggregates contain more pores and microcracks, which accelerate chloride penetration and impair the service life of buildings [6–8]. Some scholars have investigated the resistance of concrete to chloride penetration by treating concrete as a multi-phase inhomogeneous material at the mesoscale [9,10]. Xiao et al. [11] proposed a five-phase composite model with one RCA and studied chloride migration in the model using numerical analysis. Ying et al. [12] established a five-phase model with multiple spherical structures for RAC,

considering the adhesive old mortar and ITZ. Strubar III [13] proposed a one-dimensional chloride permeation modeling of RAC as a composite material composed of five phases to investigate its service life. Liu et al. [14] analyzed the impact of individual concrete components on chloride penetration using a three-phase modeling approach to simulate multiple-component ion transfer. Hu et al. [15] established a stochastic five-phase model for RAC to quantitatively analyze each phase's impact upon RAC's effective chloride spreading rate. Yu and Lin [16] defined RAC as a three-phased composite and investigated the effects of key parameters on chloride diffusion. Additionally, an approach based on genetic programming was proposed to forecast the permeability of RAC. Wu et al. [17] developed a convex polygon computational model by considering RAC as a seven-phase composite structure containing cracks and damage zones. In summary, most relevant studies adopt Fick's second law as the core governing equation. Researchers have established multiphase inhomogeneous models to reconstruct the mesostructural features of RAC, which can effectively characterize internal chloride diffusion behavior. Nevertheless, the majority of these numerical studies lack adequate experimental validation. Furthermore, they ignore the coupled effects of freeze-thaw cycles and supplementary cementitious materials on chloride diffusion, limiting their reliability for predicting long-term concrete durability under actual engineering service environments.

Concrete structures in cold regions are susceptible to freeze-thaw damage. During freeze-thaw cycles, the freezing of pore water generates hydraulic and crystallization pressures, which induce microcracking and cumulative deterioration in concrete. It is crucial to analyze the characteristics of chloride penetration in concrete exposed to freeze-thaw cycles [18–22]. Kuosa et al. [23] conducted field and laboratory tests to investigate the effects of freeze-thaw and chloride migration on concrete durability. The results indicated that freeze-thaw-induced microcracks significantly accelerate chloride ingress in concrete. Jiang et al. [24] proposed a three-phase mesoscale method by introducing time-varying porosity to study chloride diffusion under freeze-thaw conditions. Qiang et al. [25] calculated the total charge to explore the variation in concrete chloride content during freeze-thaw cycles with partial cement substitution by fly ash or silica fume. Yin et al. [26] conducted pull-out and flexural tests to evaluate the performance of textile-reinforced concrete under freeze-thaw damage. The study found that the mechanical properties decreased significantly with the increase of freeze-thaw cycles, especially after 90 cycles. Gao et al. [27] established a multi-phase chloride diffusion model for concrete under freeze-thaw cycles by considering the evolution of pore structure and cracks, and validated the model with third-party test data. Wang et al. [28] carried out chloride transport tests considering the combined effects of dry-wet ratio and freeze-thaw cycles. The experimental results showed that the relative error between measured data and the proposed empirical prediction values of chloride concentration was less than 15%. Existing studies have achieved fruitful outcomes, yet systematic research combining experimental testing and numerical simulation to explore the chloride diffusion behavior of RAC under freeze-thaw cycles remains scarce. Therefore, it is necessary to conduct both experimental and numerical investigations to analyze the chloride diffusion process of RAC under freeze-thaw conditions.

In previous studies, many existing chloride penetration models for RAC adopted third-party experimental data to validate the simulated results. In this study, a five-phase mesoscale model was developed by setting a specific diameter for coarse aggregate. The single-side salt freeze-thaw test was employed to validate the simulated values. This study aims to investigate the effects of different RCA substitution ratios, as well as varying dosages of fly ash and superfine fly ash, on chloride concentration in RAC. Additionally, the effects of the key model components on chloride concentration were further explored.

2. The Basics of Numerical Simulation

2.1. Chloride Migration Theory

When the RAC is wholly saturated, the chloride migration is solely determined by diffusion. Fick's second law states that the behavior of chloride diffusion can be described by Equation (1):

$$\frac{\partial C_s(x_0, y_0, t_0)}{\partial t_0} = D_p \left(\frac{\partial C_s(x_0, y_0, t_0)}{\partial x_0^2} + \frac{\partial C_s(x_0, y_0, t_0)}{\partial y_0^2} \right) (p = 1, 2, 3, 4, 5) \quad (1)$$

where t_0 is the time of chloride penetration (s), x_0 is the depth of chloride penetration (m), $C_s(x_0, y_0, t_0)$ is the chloride concentration at time t_0 and position (x_0, y_0) (%), D_p is the chloride diffusion coefficient of phase p (new mortar, old mortar, new ITZ, old ITZ, and original aggregate) (m^2/s).

To improve the convenience of model analysis, two specific conditions were defined with the following equations:

$$C_s(x_0, y_0, 0) = 0 \quad (2)$$

$$C_s(0, y_0, t_0) = C_t \quad (3)$$

where C_t is the chloride concentration at the model's boundary (%).

2.2. Recycled Aggregate Gradation

Walraven presented the area distribution of coarse aggregate on a two-dimensional plane based on Fuller's three-dimensional aggregate grading curve [29]. This can be calculated using Equation (4):

$$P_m(D < D_c) = P_s \left(1.065 D_c^{0.5} D_{max}^{-0.5} - 0.053 D_c^4 D_{max}^{-4} - 0.012 D_c^6 D_{max}^{-6} - 0.045 D_c^8 D_{max}^{-8} + 0.025 D_c^{10} D_{max}^{-10} \right) \quad (4)$$

where P_m is the possibility of the coarse aggregate diameter in $D < D_c$ range, P_s is the volume fraction of coarse aggregate, D_c is the coarse aggregate diameter (mm), D_{max} is the maximum diameter of coarse aggregate (mm).

The area of coarse aggregate in different diameter ranges was determined using Equation (5):

$$S_c[D_i, D_{i+1}] = \frac{P_m(D_{i+1}) - P_m(D_i)}{P_m(D_{max}) - P_m(D_{min})} \times S_b \times S_a \quad (5)$$

where S_c is the area of coarse aggregate in $[D_i, D_{i+1}]$ diameter range (mm^2), S_b is the proportion of coarse aggregate area, S_a is the model area (mm^2), D_{min} is the minimum diameter of coarse aggregate (mm).

2.3. Five-Phase Mesoscale Model of RAC

The five-phase mesoscale model configured with 100% RCA was developed using MATLAB R2020a and subsequently imported into COMSOL Multiphysics 5.6, as shown in Figure 1. It comprised new mortar, adhesive old mortar, new ITZ, old ITZ, and original aggregate, with dimensions of $100 \text{ mm} \times 100 \text{ mm}$. The coarse aggregate diameters ranged from 5 mm to 20 mm. To simplify the modeling process, three specific diameters of coarse aggregate (7 mm, 12 mm, and 17 mm) were selected. The left boundary of the model was designated as the region for chloride penetration.

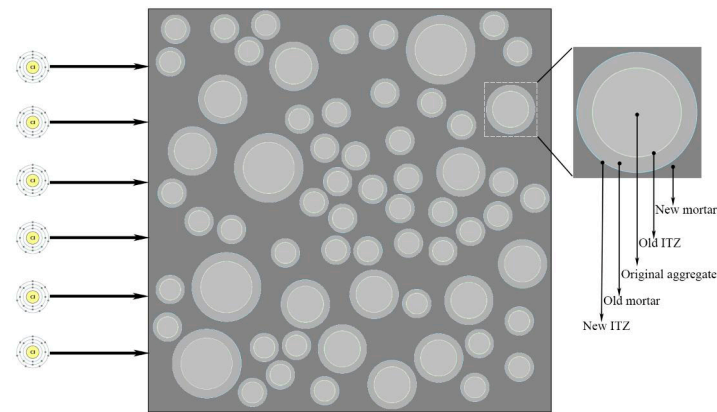


Figure 1. Schematic diagram of five-phase mesoscale model configured with 100% RCA.

2.4. Parameter Setting

RAC is an inhomogeneous material with different chloride diffusion coefficients among its components. RCA sourced from parent concrete may contain residual chloride ions. Given the diverse sources of RCA, the initial chloride ions inside aggregates were not incorporated into the model. The chloride diffusion coefficient of new mortar can be calculated as follows [30]:

$$D_{nm} = \frac{2\varnothing_p^{2.75}D_t}{\varnothing_p^{1.75}(3 - \varnothing_p) + 14.44(1 - \varnothing_p)^{2.75}} \quad (6)$$

where D_t is the chloride diffusion coefficient in the pore solution, and $D_t = 1.07 \times 10^{-10} \text{ m}^2/\text{s}$, $\varnothing_p$ is the new mortar porosity, and $\varnothing_p$ is determined as follows [31]:

$$\varnothing_p = \frac{w/b - 0.17\gamma}{w/b + 0.32} \quad (7)$$

where w/b is the water-binder ratio, γ is the hydration level, with a scale from 0 to 1.

In reference [11], it was mentioned that the chloride diffusion coefficient of old mortar was 0.2 to 5 times higher than that of new mortar. Additionally, the chloride diffusion coefficient of ITZ was reported to be 1.3 to 16.2 times that of mortar. In this study, the chloride diffusion coefficient of old mortar was two times higher than that of new mortar, and the chloride diffusion coefficient of ITZ was ten times higher than that of mortar, which is consistent with the values adopted in references [15,17]. By contrast, original aggregates have an extremely low chloride diffusion coefficient, which is set to $0 \text{ m}^2/\text{s}$ in this study. As a result, the chloride concentration inside original aggregates remains zero, and this assumption may slightly affect chloride diffusion pathways.

3. Experimental Program

3.1. Materials and Mix Proportions

This study adopted P·O 42.5 cement. Fly ash was supplied from a local concrete company and meets Grade I requirements specified in GB/T 1596-2017 standard [32]. Superfine fly ash was prepared by grinding fly ash in a ball mill. The chemical compositions of cement and fly ash are shown in Table 1. Natural coarse aggregates (NCA) consisted of gravel with diameters ranging from 5 mm to 20 mm. RCA was sourced from C&DW and had the same diameter range, with an old mortar content of 44.8%. The physical properties of coarse aggregates are shown in Table 2. Fine aggregates were obtained from river sand with an apparent density of 2620 kg/m^3 and a fineness modulus of 2.8. The water-binder ratio was 0.4. The mix proportions of RAC are shown in Table 3.

Table 1. Chemical compositions of cement and fly ash (%).

Composition	SiO ₂	Al ₂ O ₃	CaO	MgO	SO ₃	Fe ₂ O ₃	Na ₂ O	Loss
Cement	21.35	5.19	62.17	2.18	2.65	3.48	0.23	1.47
Fly ash	51.76	29.31	5.68	0.84	1.52	4.93	0.21	2.91

Table 2. Physical properties of coarse aggregates.

	Particle Size (mm)	Apparent Density (kg/m ³)	Water Absorption (%)	Crushing Value (%)
NCA	5–20	2670	0.5	7.9
RCA	5–20	2580	4.8	16.3

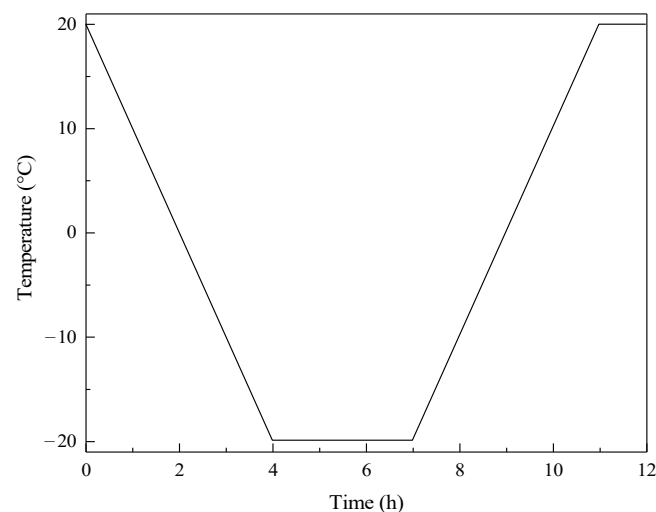
Table 3. Mix proportions of RCA (kg/m³).

	Water	Cement	Fly Ash	Superfine Fly Ash	Sand	NCA	RCA
FA0R0	175	438	0	0	572	1216	0
FA15R0	175	372	66	0	572	1216	0
SF15R0	175	372	0	66	572	1216	0
FA0R25	175	438	0	0	572	912	304
FA15R25	175	372	66	0	572	912	304
FA30R25	175	306	132	0	572	912	304
SF15R25	175	372	0	66	572	912	304
SF30R25	175	306	0	132	572	912	304
FA15R50	175	372	66	0	572	608	608

FAx: The substitution level of cement by fly ash. SFx: The substitution level of cement by superfine fly ash. Rx: The substitution level of NCA by RCA.

3.2. Salt Freeze-Thaw

The single-side salt freeze-thaw method was adopted in accordance with GB/T 50082-2009 [33]. The RAC specimens, with dimensions of 100 mm × 100 mm × 100 mm, underwent a 24-day curing process in an environment maintained at 20 ± 2 °C and 95% relative humidity. To ensure one-dimensional chloride penetration, the specimens were coated with epoxy resin on four surfaces and then immersed in water for four days. Subsequently, the specimens were subjected to freeze-thaw cycles in a box with 3% sodium chloride solution. The test was terminated after 120 freeze-thaw cycles, with a total test duration of 60 days. The freeze-thaw process is shown in Figure 2.

**Figure 2.** Freeze-thaw process.

3.3. Compressive Strength

After 120 freeze-thaw cycles, the compressive strength of the specimens was measured using a universal testing machine, with the loading rate controlled at 0.5 MPa/s. The final compressive strength value was taken as the arithmetic average of test results from three parallel specimens.

3.4. Relative Dynamic Elastic Modulus

The relative dynamic elastic modulus E_f is calculated by the following equation:

$$E_f = \frac{f_n^2}{f_0^2} \times 100 \quad (8)$$

where f_0 is the transverse fundamental frequency of the specimen before freeze-thaw cycles (Hz), and f_n is the transverse fundamental frequency of the specimen after n freeze-thaw cycles (Hz).

3.5. Mass Loss

The mass loss M_n is calculated by the following equation:

$$M_n = \frac{G_0 - G_n}{G_0} \times 100 \quad (9)$$

where G_0 is the mass of the saturated specimen (g), and G_n is the mass of the specimen subjected to n freeze-thaw cycles.

3.6. Chloride Content

Specimens were taken out of the freeze-thaw testing machine, and successive 5 mm-thick layers were precisely chipped off from the erosion surface before being ground into fine powder with an agate mortar and pestle. The powder was sieved through a 0.16 mm sieve for subsequent testing. The test procedures followed JGJ/T 322-2013 [34], and the chloride content in RAC was calculated by using Equation (10):

$$P_h = \frac{C_{AgNO_3} \times V_1 \times V_2 \times 0.03545}{m_0 \times V_3} \times 100\% \quad (10)$$

where P_h is the chloride content in RAC (%), C_{AgNO_3} is the concentration of silver nitrate solution (mol/L), m_0 is the sample powder mass (g), V_1 is the consumption of silver nitrate solution (mL), V_2 is the volume of distilled water (mL), V_3 is the filtrate volume (mL).

4. Results

4.1. Compressive Strength

Table 4 shows the compressive strength results of all specimens after 120 freeze-thaw cycles. FA0R0 exhibits the highest compressive strength of 46.7 MPa. At a 15% dosage of fly ash or superfine fly ash, the compressive strength values of FA15R0 and SF15R0 decrease to 41.9 MPa and 39.5 MPa. At a 25% RCA substitution ratio, FA0R25 yields a compressive strength of 37.8 MPa. The compressive strength of FA15R25 increases to 42.6 MPa, whereas that of SF15R25 reaches 38.4 MPa. When the fly ash or superfine fly ash dosage is elevated to 30%, the compressive strength values of FA30R25 and SF30R25 drop to 29.1 MPa and 28.2 MPa. Among all specimens, FA15R50 exhibits the lowest compressive strength at merely 26.8 MPa. These observed strength variation trends clearly reflect the influences of RCA substitution ratio and fly ash/superfine fly ash dosage on the compressive strength of specimens after freeze-thaw cycles.

Table 4. Compressive strength of all specimens after 120 freeze-thaw cycles.

	FA0R0	FA15R0	SF15R0	FA0R25	FA15R25	FA30R25	SF15R25	SF30R25	FA15R50
Compressive strength (MPa)	46.7	41.9	39.5	37.8	42.6	29.1	38.4	28.2	26.8

4.2. Relative Dynamic Elastic Modulus

Table 5 shows the relative dynamic elastic modulus results for all specimens subjected to 30, 60, 90, and 120 freeze-thaw cycles. For all specimens, the relative dynamic elastic modulus exhibits a gradual downward trend as the number of freeze-thaw cycles increases. After 120 freeze-thaw cycles, the corresponding values fall within the range of 53% to 66%. Specifically, the relative dynamic elastic modulus of FA0R0 drops to 66%, whereas that of all other specimens is lower. FA30R25, SF30R25 and FA15R50 consistently show relatively lower values. Overall, the variation pattern of relative dynamic elastic modulus across all specimens after 120 freeze-thaw cycles is broadly consistent with the trend of compressive strength.

Table 5. Relative dynamic elastic modulus results for all specimens.

	FA0R0	FA15R0	SF15R0	FA0R25	FA15R25	FA30R25	SF15R25	SF30R25	FA15R50
0	100%	100%	100%	100%	100%	100%	100%	100%	100%
30	99%	98%	98%	97%	99%	94%	96%	93%	92%
60	91%	89%	87%	88%	89%	82%	86%	81%	83%
90	79%	76%	75%	73%	74%	68%	72%	70%	69%
120	66%	64%	62%	61%	60%	54%	59%	53%	55%

4.3. Mass Loss

Table 6 shows the mass loss of all specimens after 30, 60, 90 and 120 freeze-thaw cycles. As the number of freeze-thaw cycles increases, the mass loss of all specimens gradually shifts from negative to positive values, indicating that the specimen mass generally follows a trend of initial increase followed by decrease. After 120 freeze-thaw cycles, FA30R25, SF30R25 and FA15R50 exhibit relatively higher mass loss, which is generally consistent with the variation trend of the relative dynamic elastic modulus.

Table 6. Mass loss of all specimens.

	FA0R0	FA15R0	SF15R0	FA0R25	FA15R25	FA30R25	SF15R25	SF30R25	FA15R50
30	−0.9%	−0.7	−1.0%	−1.2%	−0.8%	−1.3%	−0.6%	−1.1%	−1.4%
60	−0.2%	−0.3%	−0.1%	0.2%	0.1%	0.4%	0.3%	0.6%	0.7%
90	0.6%	0.8%	0.9%	1.1%	1.2%	2.0%	1.3%	2.2%	1.9%
120	1.8%	2.1%	2.3%	2.5%	2.6%	3.5%	2.8%	3.6%	3.4%

5. Validation and Discussion

The simulated values were averaged across three locations at the same depths. Freeze-thaw cycles can significantly accelerate the process of chloride penetration process within concrete. According to Fick's second law, the chloride concentration of concrete is determined by the chloride diffusion coefficient and diffusion time. Freeze-thaw exposure increases the chloride diffusion coefficient of each phase in concrete to varying degrees; therefore, the chloride penetration effect under freeze-thaw conditions can be equivalently regarded as the result of natural diffusion over a longer duration. Upon completing 120 freeze-thaw cycle tests, a comparative analysis of the measured chloride data against COMSOL simulation results was performed. The comparison indicates that the penetration

effect observed in the test corresponds to approximately 800 days of penetration in the mesoscale model. After repeated comparisons, it is finally confirmed that the highest degree of agreement between simulated and experimental values is achieved when the penetration time is set to 780 days. The numerical parameters of the RAC model are shown in Table 7. Figure 3 shows the chloride concentration distribution in RAC at RCA substitution ratios ranging from 0–50%.

Table 7. Numerical parameters of the RAC model.

Symbol	Parameter	Value
T_d	Diffusion time	780 days
V_p	Volume fraction of coarse aggregate	47%
α_s	Adhesive rate of old mortar	0.45
w/b	Water-binder ratio	0.4
D_{nm}	Chloride diffusion coefficient of new mortar	$3.8553 \times 10^{-12} \text{ m}^2/\text{s}$
D_{om}	Chloride diffusion coefficient of old mortar	$7.7106 \times 10^{-12} \text{ m}^2/\text{s}$
D_{ni}	Chloride diffusion coefficient of the new ITZ	$3.8553 \times 10^{-11} \text{ m}^2/\text{s}$
D_{oi}	Chloride diffusion coefficient of the old ITZ	$7.7106 \times 10^{-11} \text{ m}^2/\text{s}$
D_{agg}	Chloride diffusion coefficient of original aggregate	$0 \text{ m}^2/\text{s}$
T_{ni}	Thickness of the new ITZ	$100 \text{ }\mu\text{m}$
T_{oi}	Thickness of the old ITZ	$100 \text{ }\mu\text{m}$

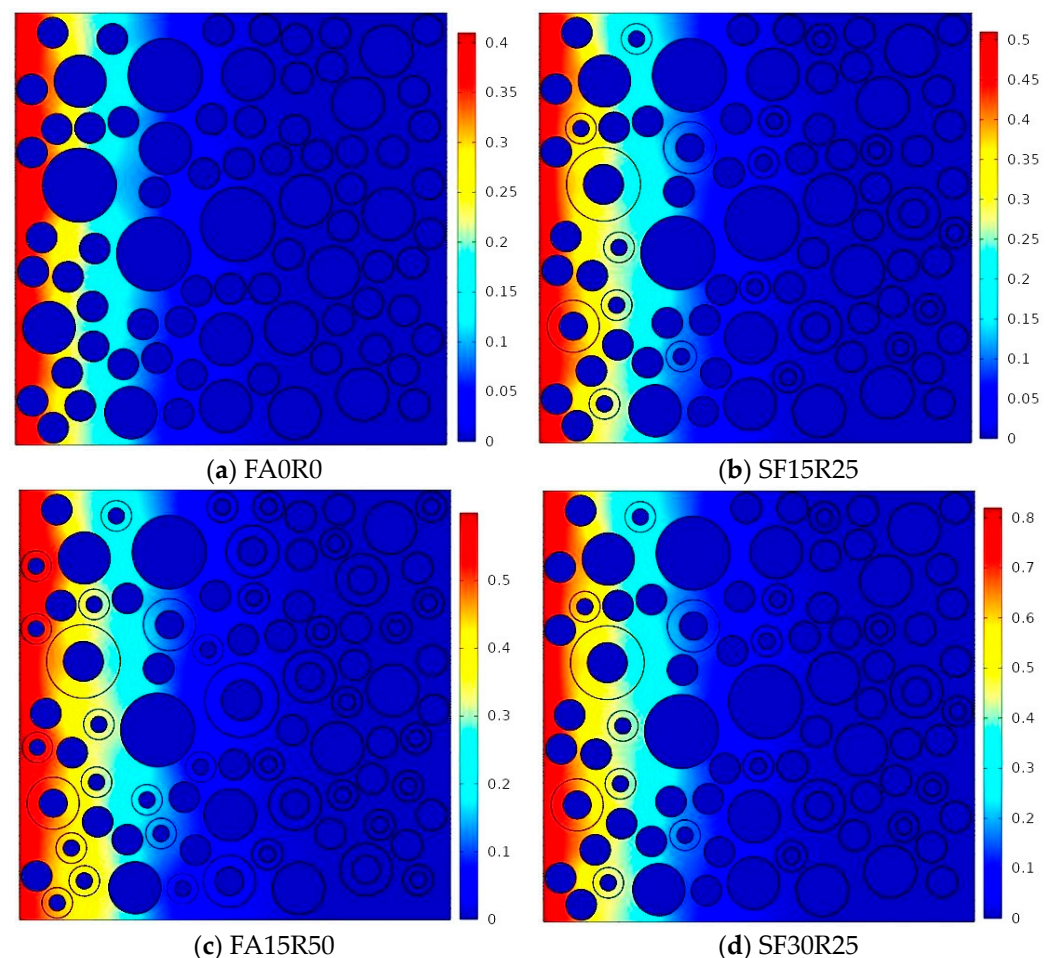


Figure 3. Chloride concentration distribution at RCA substitution ratios ranging from 0–50%.

5.1. Effect of RCA Substitution Ratios on Chloride Concentration

Figure 4 shows the comparison of chloride concentration between experimental data and simulated values at different RCA substitution ratios. The error bars in all figures

represent the standard deviation of triplicate test results ($n = 3$). The experimental data for FA0R0 and FA0R25 closely align with the simulated values. However, the experimental data for FA15R0, FA15R25, and FA15R50 are lower than the simulated values. Adding 15% fly ash to RAC enhances its resistance to chloride penetration. This enhancement is attributed to the pozzolanic reaction of fly ash, which facilitates the formation of hydrated calcium silicate (C-S-H) gel. Consequently, the concrete becomes denser, leading to a reduction in chloride concentration. This elucidates why the experimental data for FA15R0, FA15R25, and FA15R50 are lower than the simulated values.

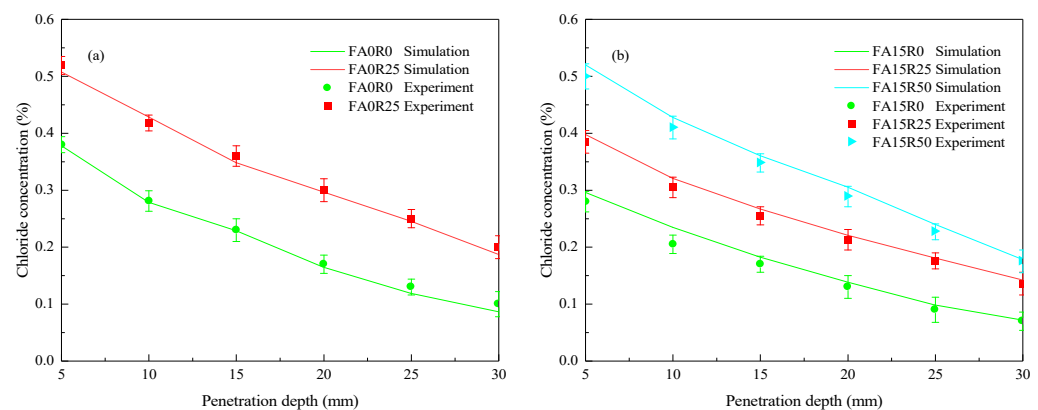


Figure 4. Comparison of chloride concentration between experimental data and simulated values at different RCA substitution ratios: (a) FA0R0 and FA0R25; (b) FA15R0, FA15R25 and FA15R50.

In Figure 4a, at a depth of 5 mm, the chloride concentration from experimental data reaches 0.38% for FA0R0, while the experimental data of FA0R25 shows a chloride concentration of 0.52%. In Figure 4b, at a depth of 10 mm, the experimental data of FA15R50 exhibits an 82.61% increase in chloride concentration compared to the experimental data of FA15R0. Similarly, the experimental data of FA15R25 demonstrate a 34.78% increase in chloride concentration relative to the experimental data of FA15R0. Increasing the RCA substitution ratio reduces the resistance of RAC to chloride penetration during freeze-thaw cycles. The rising content of adhesive old mortar is the primary reason for this phenomenon, leading to increased porosity and microcracks in RAC. Freeze-thaw cycles generate new cracks and pores, providing more pathways for chloride penetration.

5.2. Effect of Fly Ash and Superfine Fly Ash Dosages on Chloride Concentration

Figure 5 shows the comparison of chloride concentration between experimental data and simulated values at varying dosages of fly ash and superfine fly ash. The experimental data for FA30R25 and SF30R25 exceed the simulated values. Adding 30% fly ash to RAC reduces its resistance to chloride penetration. Excessive fly ash impedes the hydration reaction, increasing the concrete's chloride concentration. Therefore, the experimental data for FA30R25 exceed the simulated values. In Figure 5a, the experimental chloride concentration values for FA0R0 are the highest, while those for FA15R0 show the largest drop. At a depth of 15 mm, the experimental chloride concentration reaches 0.23% for FA0R0, 0.2% for SF15R0, and 0.18% for FA15R0. In Figure 5b, FA15R25 presents the most significant reduction in experimental chloride concentration values compared with those of FA0R25, followed by those of SF15R25. SF30R25 exhibits the largest rise in experimental chloride concentration values compared with those of FA0R25, followed by those of FA30R25.

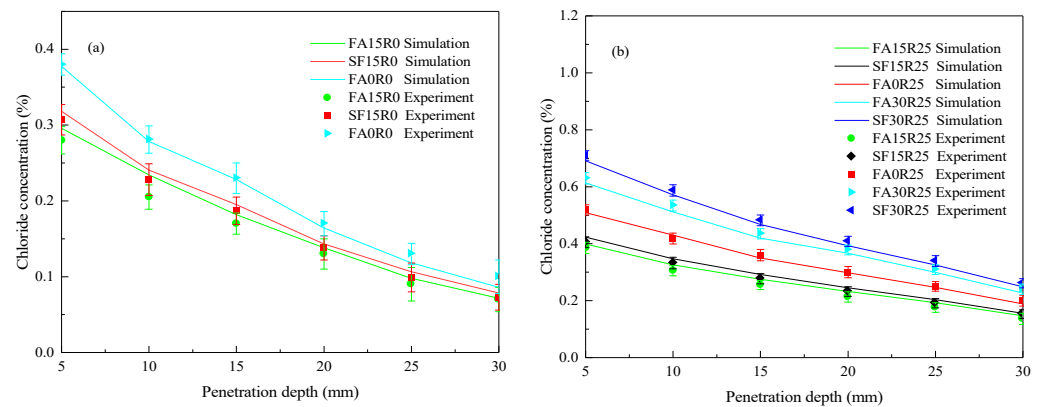


Figure 5. Comparison of chloride concentration between experimental data and simulated values at varying dosages of fly ash and superfine fly ash: (a) FA15R0, SF15R0 and FA0R0; (b) FA15R25, SF15R25, FA0R25, FA30R25 and SF30R25.

6. Simulation and Discussion

The RCA volume fraction, ITZ thickness, and adhesive ratio of old mortar were further analyzed quantitatively. It was assumed that the new ITZ thickness was equal to that of the old ITZ. The chloride concentration at the model's boundary was set at 1.5%. The chloride diffusion coefficients of the model are shown in Table 8.

Table 8. Chloride diffusion coefficients of the model.

Symbol	Parameter	Value
D_{nm}	Chloride diffusion coefficient of new mortar	$5.4492 \times 10^{-12} \text{ m}^2/\text{s}$
D_{om}	Chloride diffusion coefficient of old mortar	$1.0898 \times 10^{-11} \text{ m}^2/\text{s}$
D_{ni}	Chloride diffusion coefficient of the new ITZ	$5.4492 \times 10^{-11} \text{ m}^2/\text{s}$
D_{oi}	Chloride diffusion coefficient of the old ITZ	$1.0898 \times 10^{-10} \text{ m}^2/\text{s}$
D_{agg}	Chloride diffusion coefficient of original aggregate	$0 \text{ m}^2/\text{s}$

6.1. RCA Volume Fraction

The chloride concentration distribution in RAC at different RCA volume fractions ($V_p = 15\%, 25\%, 35\%$, and 45%) after 1200 days was calculated, as shown in Figure 6. The adhesive ratio of old mortar was 0.25. Both the new and old ITZ had a thickness of $50 \mu\text{m}$. Figure 7 shows the effect of different RCA volume fractions on chloride concentration. The chloride concentration values increase with a higher RCA volume fraction. At a depth of 50 mm, the chloride concentration values are 0.23%, 0.24%, 0.27%, and 0.29%, respectively. As the RCA volume fraction increases, there is a corresponding rise in weak regions such as adhesive old mortar. Consequently, the resistance of RAC to chloride penetration decreases.

A parametric sensitivity analysis is carried out in this section to verify the reliability of the main conclusions of this paper. First, the chloride diffusion coefficient of old mortar is adjusted to 2.5 times that of new mortar, while all other parameters remain unchanged. The resulting chloride concentration distribution is shown in Figure 8. At a depth of 50 mm, the chloride concentration values are 0.24%, 0.26%, 0.29%, and 0.32%, respectively.

Then, the chloride diffusion coefficient of ITZ is adjusted to 13 times that of mortar, with all other parameters kept the same. The chloride concentration distribution is shown in Figure 9. At a depth of 50 mm, the chloride concentrations are 0.25%, 0.26%, 0.28%, and 0.31%, respectively. Overall, the core conclusion that the chloride penetration resistance of RAC decreases with increasing RCA volume fraction remains unchanged. This demon-

states that the parameter values adopted in this paper are reasonable and the research conclusions are reliable.

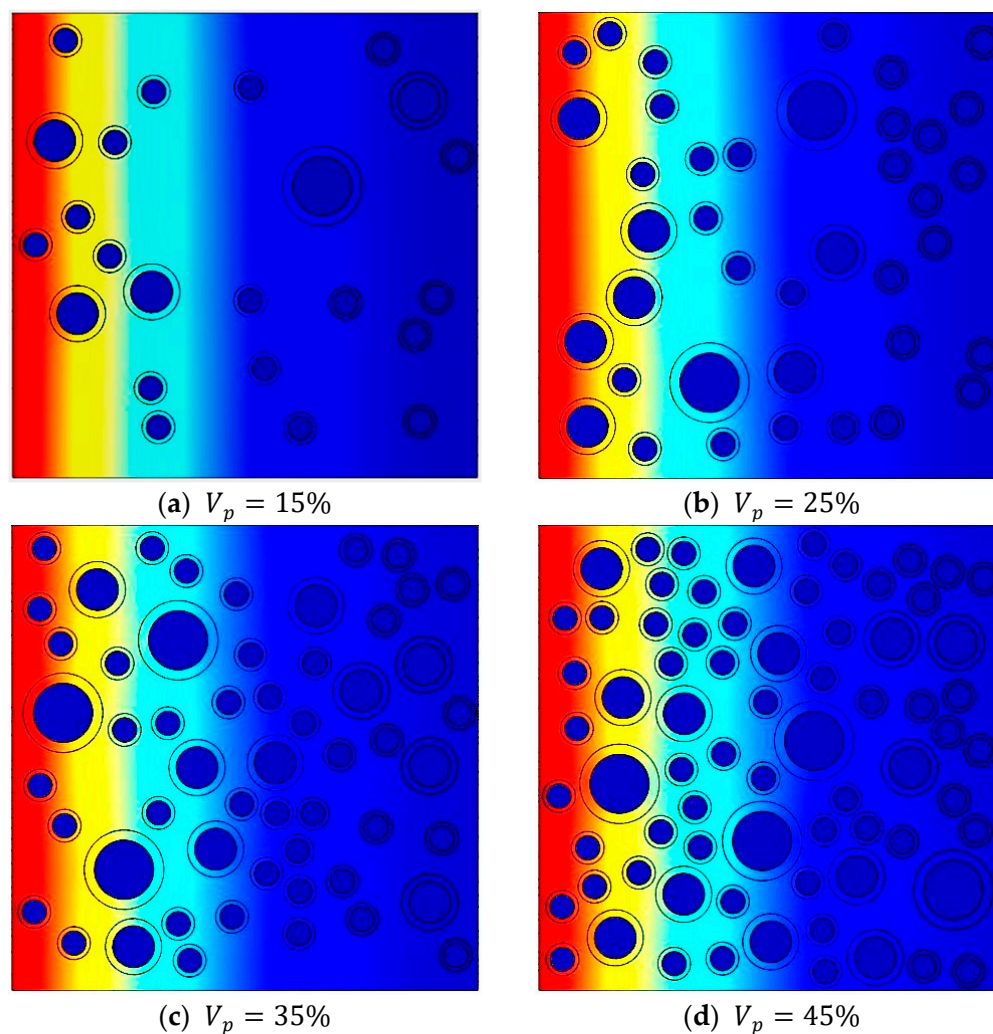


Figure 6. Chloride concentration distribution at different RCA volume fractions.

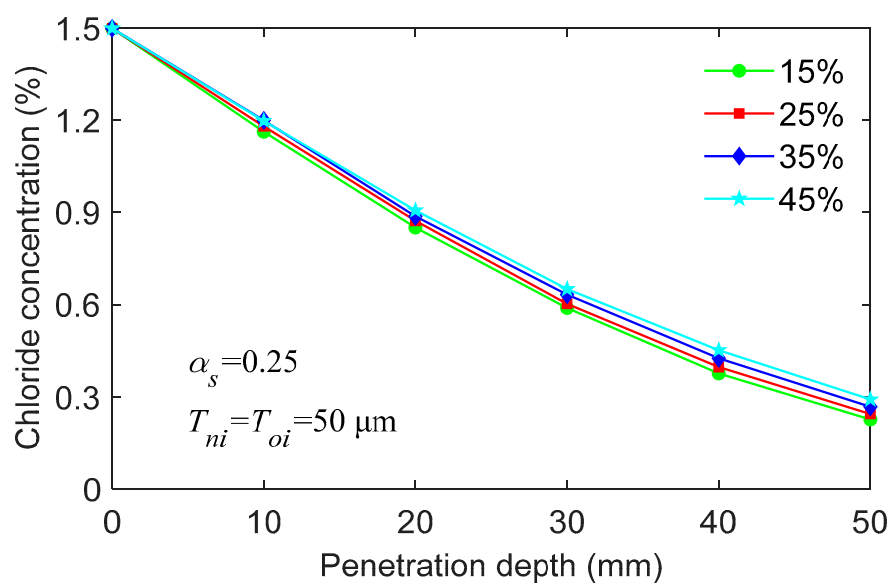


Figure 7. Effect of different RCA volume fractions on chloride concentration.

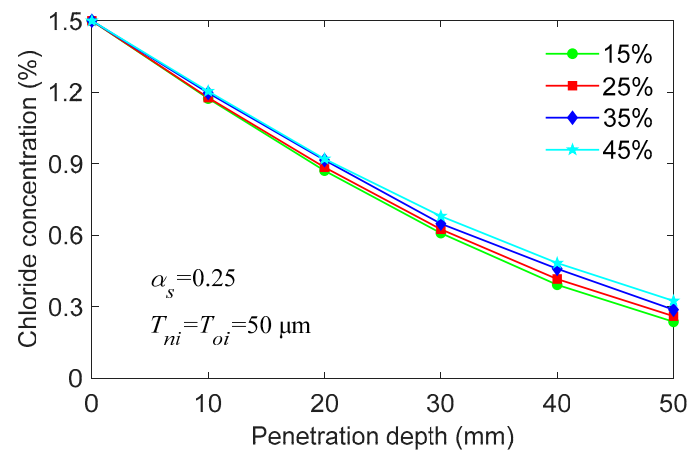


Figure 8. Chloride concentration distribution when the chloride diffusion coefficient of old mortar is 2.5 times that of new mortar.

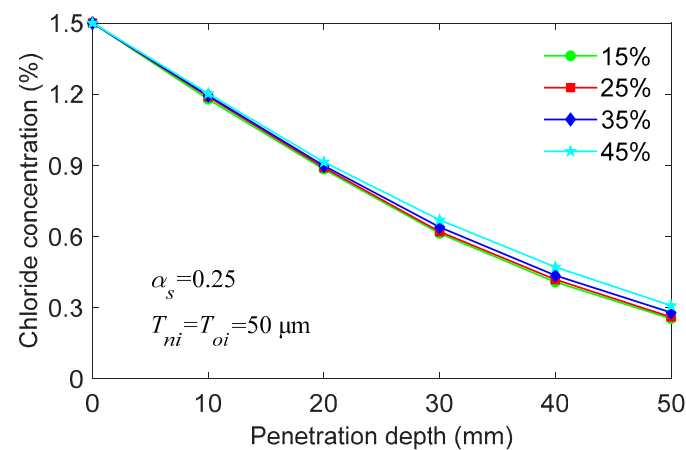


Figure 9. Chloride concentration distribution when the chloride diffusion coefficient of ITZ is 13 times that of mortar.

6.2. ITZ Thickness

While the ITZ thickness is relatively small, its effect on chloride concentration in RAC should not be underestimated. Figure 10 shows the effect of different ITZ thicknesses ($T_{ni} = T_{oi} = 30 \mu\text{m}$, $50 \mu\text{m}$, $70 \mu\text{m}$, and $90 \mu\text{m}$) on chloride concentration. As the ITZ thickness increases, there is a consistent rise in chloride concentration. At a depth of 40 mm, the chloride concentration values are 0.38%, 0.40%, 0.43%, and 0.45%, respectively. Increasing the ITZ thickness reduces the resistance of RAC to chloride penetration.

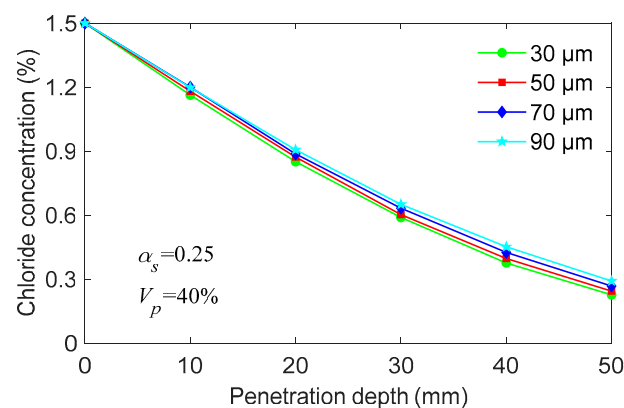


Figure 10. Effect of different ITZ thicknesses on chloride concentration.

6.3. Adhesive Ratio of Old Mortar

The chloride concentration distribution in RAC at different adhesive ratios of old mortar ($\alpha_s = 0.15, 0.25, 0.35$, and 0.45) was extracted, as shown in Figure 11. Figure 12 shows the effect of different adhesive ratios of old mortar on chloride concentration. The chloride concentration values increase as the adhesive ratio of old mortar rises. Increasing the adhesive rate of old mortar reduces the resistance of RAC to chloride penetration. At a depth of 30 mm, the chloride concentration values are 0.61%, 0.63%, 0.65%, and 0.66%, respectively. Reducing the adhesive ratio of old mortar is recommended to enhance the resistance of RAC to chloride penetration.

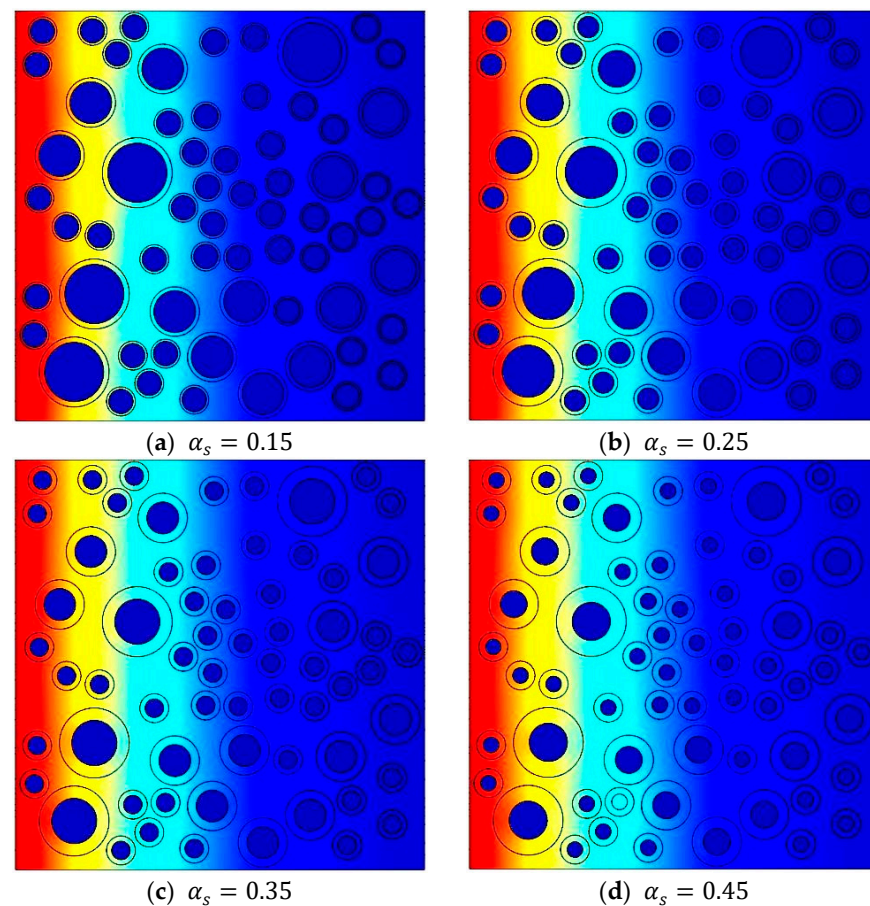


Figure 11. Chloride concentration distribution at different adhesive ratio of old mortar.

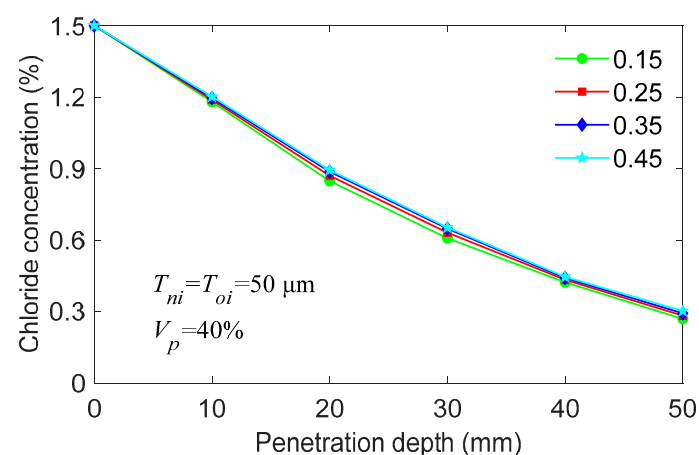


Figure 12. Effect of different adhesive ratios of old mortar on chloride concentration.

6.4. Engineering Application Suggestions for RCA

The utilization of RCA in practical engineering remarkably reduces the demand for natural aggregates, facilitates the recycling of C&DW, curbs carbon emissions, and mitigates the environmental pressure arising from C&DW landfilling, which contributes to ecological conservation. The quality of RCA can be assessed via critical indices including water absorption and crushing value. As a general rule, RCA with lower water absorption exhibits superior overall performance. Two categories of physical and chemical pretreatment approaches are available to strip old mortar from RCA surfaces for performance enhancement. Physical pretreatments cover mechanical grinding and microwave thermal treatment, while chemical modification involves immersing RCA in conditioning agents such as acidic solutions and water glass solutions. From the perspective of long-term structural service reliability, the RCA substitution ratio is suggested to be limited to 50% for on-site applications. Such a dosage threshold can effectively avoid severe degradation in concrete mechanical performance and lower potential durability hazards originating from inconsistent RCA quality.

7. Conclusions

In this study, the damage degree of RAC under salt freeze-thaw environments was characterized through the indices of compressive strength, relative dynamic elastic modulus, and mass loss. A five-phase mesoscale model of RAC was established. This study innovatively combines numerical simulation with experimental validation to investigate the effects of different RCA substitution ratios, as well as varying dosages of fly ash and superfine fly ash, on chloride concentration in RAC during freeze-thaw cycles. The main conclusions are drawn as follows:

- (1) Increasing the RCA substitution ratio significantly reduces the resistance of RAC to chloride penetration. This phenomenon is primarily attributed to increased old mortar, which contains more microcracks. Under freeze-thaw cycles, these defects are further amplified, thus forming transport pathways for chloride penetration.
- (2) Adding 15% fly ash to RAC enhances its resistance to chloride penetration, whereas adding 30% fly ash exerts a detrimental effect.
- (3) Controlling the RCA volume fraction, ITZ thickness, and adhesive ratio of old mortar at lower levels can effectively improve the resistance of RAC to chloride penetration.

Overall, this study reveals the multi-factor mechanism of chloride penetration in RAC under freeze-thaw environments through the combination of numerical simulation and experimental validation. The findings provide a quantitative theoretical basis and practical guidance for the durability design of RAC in cold regions. This study mainly explores the effects of RCA substitution ratios, fly ash, and superfine fly ash dosages on chloride concentration, with limited research variables. Future research will further improve the chloride penetration mechanism of RAC under salt freeze-thaw environments by considering more influencing factors, including freeze-thaw cycle times, chloride solution concentration, crack width, and other supplementary cementitious materials.

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