Mesoscale Simulation of Chloride Ion Diffusion in Five-phase Recycled Aggregate Concrete

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Abstract

The durability of recycled aggregate concrete (RAC) is a critical issue when using RAC in construction. Among various factors, reinforcement erosion due to chloride ion penetration is the main determinant of RAC durability. In this study, the chloride ion diffusion in RAC was systematically investigated using the COMSOL multiphysics finite element method. The RAC was described by a five-phase model, including natural aggregate, old interfacial transition zone, old mortar, new interfacial transition zone, and new mortar. The region consisting of natural aggregate, old interfacial transition zone and old mortar is called recycled aggregate. The results showed that the distribution of recycled aggregate had little effect on the diffusion of chloride ions in the RAC. The old mortar and the old interfacial transition zone, on the other hand, effectively contributed to the diffusion of chloride ions in the RAC. This effect was attributed to the porous characteristics of the old mortar and the old interfacial transition zone. An increase in the water-cement ratio significantly promoted the diffusion of chloride ions in the RAC. These results provide valuable information on the utilization of recycled aggregates, thus paving an effective path for the sustainable development in the construction industry.

Keywords

Recycled Aggregate Concrete; COMSOL Multiphysics; Chloride Diffusion; Finite Elements; Numerical Modelling.

1. Introduction

With the rapid development of urbanization, the construction industry has become a pillar industry of the national economy. The construction of new buildings and the renovation/demolition of old buildings play an important role in promoting economic growth. At the same time, a large amount of construction waste has been generated in the process of rapid urbanization [1]. It has been reported that China generates more than 2.36 billion tonnes of construction waste annually [2]. Disposal of construction waste occupies huge landfill space and can cause serious environmental problems if not handled properly. Construction waste has high recycling potential and economic value, and 80% of its components can be reused [3]. The use of construction waste as recycled aggregates in recycled aggregate concrete (RAC) can reduce the extraction of natural aggregates, which is a ‘kill two birds with one stone’ strategy to achieve sustainable development in the construction industry [4-6].

The durability of RAC is a major issue in recycled aggregate applications [7]. An important factor affecting the durability of RAC is corrosion of reinforcement by chloride ion penetration [8]. It is essential to understand the diffusion mechanism of chloride ion diffusion in RAC and the factors affecting it. Many studies have used experimental and numerical methods to determine the diffusion coefficients of chloride ions in RAC. Mao [9] studied the migration of chloride ions in different types of RACs. Vazquez [10] investigated the effect of different water-cement ratios (w/c) and percentages of natural aggregates on the diffusion of chloride ions, and found that RACs with a high natural aggregate and a low w/c ratio had a higher durability. Bao [11] reported that the chloride ion content and penetration depth of RACs increased significantly with the increase of natural aggregates. Zhang [12] and Jin [13] tested the effect of chloride diffusion under freeze-thaw and dry-wet cycling conditions, respectively, and found that both factors caused damage to recycled aggregate and accelerated chloride ion penetration.

A lot of experimental results have been obtained on the influence of different factors on the chloride permeation and other performance of RAC, but little research has been done on the interaction of diffusion coefficients between different phases of RAC, especially the transition zone between the old mortar and the interfacial transition zone (ITZ). Due to experimental limitations, it is a great challenge to evaluate the exact differences in diffusion coefficients in the above-mentioned transition zones. However, numerical simulations can compensate for the experimental limitations. The structure of RAC is more complex than that of natural aggregate concrete. A good mesoscopic model is the to obtain accurate results from numerical simulations. For natural aggregate concrete, two-phase[14], three-phase [15, 16] and five-phase [13, 17, 18] model are usually used. As for RAC, due to its complex structure, it is usually described by five-phase [19], six-phase [20] and seven-phase [20]. Many scholars have obtained good results in the durability of RAC through numerical calculations [13, 21, 22]. Shi [4] used a two-parameter model to predict the chloride ion penetration resistance of RAC based on a quantitative analysis of the relationship between the diffusion coefficient and the porous structure. Xiao [19] proposed a monolithic RAC model based on the multiphase theory and the finite element method in order to investigate the effect of different phases of RAC. Ying [21] analyzed the relationship between diffusion coefficients and residual old mortar, aggregate substitution rate, and the thicknesses of the old interfacial transition zone (OITZ) and the new interfacial transition zone (NITZ) by using a five-phase model. Hu [23] analyzed the relationship between the effective diffusion coefficients of the five phases of RAC. Wu [22] reported that he number, orientation, and length of microcrack defects had a significant effect on the diffusion parameter of chloride ions in RAC. Jin [20] proposed a random convex polygonal recycled aggregate and analyzed the effects of cracks and damage zones on the penetration of chloride ions into the cracked RAC. The results showed that the damage zone accelerated the penetration of chloride ions, and the crack length was more critical than the crack width on the penetration of chloride ions. Among various numerical simulations, finite element simulations have also made progress in this area. Li [24] modeled OITZ and new mortar paste in RAC based on the CEMHYD3D software. Kang [2] studied the effect of zonal distribution between the recycled aggregate and the new mortar on chloride ion migration. This work provided technical support for the study of durability of concrete structures. Yu effectively studied the chloride ion diffusion coefficients and their influencing factors by using the finite element method and the genetic planning method. However, to the best of our knowledge, no study has addressed how the transition zone between old mortar and the recycled aggregate affects the chloride diffusion.

Here, we intend to investigate the chloride diffusion in RAC using the finite element method. We considered five factors including the distribution of recycled aggregate, fine structures, old mortar, OITZ and water-cement ratio. The work is organized as follows: first, a five-phase model including natural aggregate, old mortar, new mortar, NITZ and OITZ is proposed; then the reliability of the model is verified based on the comparison of simulations and experimental results; and finally, the effects of different factors are discussed based on the simulation results.

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2. Theory, Modelling and Simulations

2.1 Theory of Chloride Ion Migration in RAC

The migration of chloride ions in RAC under saturated conditions is based on Fick's second law, which is analogous to heat conduction. The main driving force for chloride ion migration can be expressed as [16]:

$$\frac{\partial C}{\partial t} = D_i \frac{\partial^2 C}{\partial x^2} \tag{1}$$

where C represents the concentration of chloride ions in the cement paste matrix, %; x represents the diffusion distance of chloride ions in the RAC, D_i represents the diffusivity of chloride ions in a particular phase.

The use of Fick's second law assumes that RAC is a semi-infinite homogenous permeant in which chloride ions diffuse without reacting and that the diffusion coefficient D_i is constant. The concentration of chloride ions at different time and depths can be calculated as follows [16]:

$$C(x, y, t) = C_0 + (C_s - C_0)\left[1 - \mathrm{erf}\left(\frac{x}{2\sqrt{D_a t}}\right)\right] \tag{2}$$

where C_s is the chloride ion concentration at the RAC surface, %; C_0 is the initial chloride ion concentration, %; $\mathrm{erf}(x/2\sqrt{D_a t})$ is the error function; and Da represents the apparent diffusion coefficient of chloride ions in RAC, m²/s.

2.2 Modelling

(1) Mesoscopic model of RAC

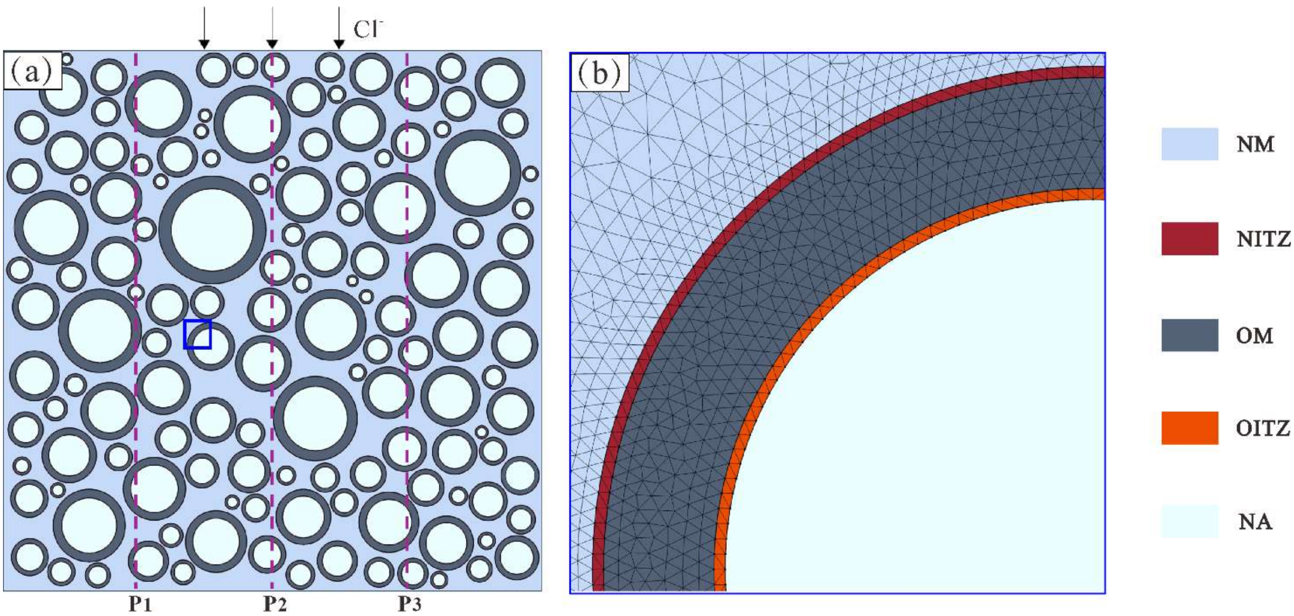

Fig. 1 (a) Mesoscopic model of RAC consisting of natural aggregate (NA), old interfacial transition zone (OITZ), old mortar (OM), new interfacial transition zone (NITZ), and new mortar (NM). The three phases of NA, OITZ and OM make up the recycled aggregate. P_1, P_2, and P_3 represent the locations where chloride ion diffusion was measured. (b) Enlarged view of the zone enclosed with blue square. The meshing was performed using a free triangular grid with 524635 meshes and 74824 boundaries.

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For mesoscopic modelling of fresh concrete consists of three main phases including the aggregate, mortar and interface between them. For recycled aggregate concrete, the issue is more complex due to the presence of the old mortar around the aggregate particles and the interface between the old mortar and the new mortar. In order to describe the RAC model more accurately, two additional parameters must be considered, namely the OM remaining around the recycled aggregate and the OITZ between the natural aggregate and the old mortar. Here, the RAC model is described in terms of five phases, including the natural aggregate (NA), the old interfacial transition zone (OITZ), the old mortar (OM), the new interfacial transition zone (NITZ), and the new mortar (NM). The same model was used in the study of Hu [23]. In this model, each phase is continuous and has its own unique diffusion coefficient. A representative 100 mm × 100 mm model is shown in Fig. 1.

The content of the old mortar can be derived from the binding ratio (R_{rm}), which can be defined as the ratio of the thickness of the old mortar to the radius of the recycled aggregate particles. Here, the recycled aggregate content is 50% and the binding ratio of OM is 40%. Xie [25]reported that the thickness of OITZ and NITZ falls between 10-100 um. The thickness of OITZ and NITZ was set to 100 um. The particle size of the aggregate is described by the Fuller curve. The sieving method is used to determine the distribution of aggregates with different particle sizes. The particles are randomly distributed in the mortar matrix to ensure that overlap between neighboring aggregate particles is avoided.

(2) Diffusion coefficients of chloride ions in different phases of RAC

The concrete is considered to be fully saturated, and only diffusion occurs between the seawater and concrete. In order to simulate the chloride ion diffusion in RAC, it is essential to determine the values of diffusion coefficients in each phase RAC.

(a) Natural aggregate

The transition of chloride ions in RAC is closely related to the porosity of the component phase. Compared to the other four phases, the particles of natural aggregate in RAC are dense, the chloride ion diffusion in this phase can be neglected. Therefore, the diffusion coefficient of chloride ions in natural aggregate is set to zero.

(b) New mortar

A hardened cement paste consists of unhydrated cement particles, hydration products and pores filled by seawater and air. A number of empirical equations have been proposed to describe the relationship between the diffusion coefficient and porosity of a cement paste. The diffusion coefficient of chloride ions in new mortar (D_{nm}) is expressed as [26]:

$$D_{nm} = \frac{2\varphi_p^{2.75} D_p}{\varphi_p^{1.75}(3-\varphi_p)+n(1-\varphi_p)^{2.75}} \tag{3}$$

where φ_p is the porosity of the cement mortar; D_p denotes the diffusion coefficient of chloride ions in the seawater filled in the pores, and the value of D_p is 1.07×10^{-10} m²/s; n is the fitting constant, and the value is 14.44, and n is the same as the one used by Zheng and Zhou [13].

The value of φ_p can be calculated by the following equation [26].

$$\varphi_p = \frac{w/c-0.17h}{w/c+0.32} \tag{4}$$

where w/c is the water-cement ratio, h is the degree of hydration, and the value of h ranges from 0 to 1.

(c) Old mortar

To date, few studies have been conducted on the diffusion of chloride ions in old mortar. Ratios of diffusion coefficients between old mortar and new mortar have been reported to be in the range of 0.2 to 5 [19]. For example, Jin [13, 20]used a ratio of 2 in their studies. Here, a series of ratios of 2, 3, 4, and 5 were set to study the effect of old mortar on the diffusion of chloride ions. The erosion time was set at 235 and 730 days, respectively.

(d) Old interfacial transition zone

Assuming that the thickness of the NITZ and OITZ are equal, both being 100 μm. The porosity of both the NITZ and OITZ is greater than that of the new and old mortar, which leads to an increase in the diffusion coefficient of chloride ions. For ordinary cement, the diffusion coefficient of chloride ions in the ITZ is 1.3 to16.2 times higher than that in mortar[13, 20]. Therefore, the ratio of the chloride diffusion coefficient of NITZ/OITZ to that of the new/old mortar was set to 10. For further discussion of the effect of OITZ on chloride diffusion, the ratios were set to 4, 8, 12, and 16, and the erosion time was set to 235 and 730 days, respectively.

2.3 Simulations

The diffusion of chloride ions in the RAC can be calculated using the Dilute Species Transport Module integrated in the COMSOL Multiphysics software [27-30].All simulations were carried out using COMSOL Multiphysics finite element software with a free-triangle mesh. The diffusion coefficients of chloride ions in each phase were determined from experimental data and literature sources and then input into the finite element model. The numerical simulation results were compared with other experimental data to validate the reliability of the finite element model. The validated numerical model was used to simulate the diffusion of chloride in different samples. The effect of different factors on the chloride diffusion in RAC was discussed based on the results. In order to further discuss the overall effect of different factors, the cumulative concentration, Sc was also introduced. The Sc value was calculated using the following equation [31]:

$$S_c = \iint_{\Omega} C(x, y, t)\,dxdy \tag{5}$$

where C(x,y,t) is the spatial distribution of chloride ion concentration at time t and Ω is the calculation region.

3. Results and Discussion

3.1 Validation of the Finite Element Model

In order to verify the reliability of the finite element modelling, the diffusion of chloride ions was calculated using the mesoscale model of COMSOL. The diffusion coefficient ratios of between old and new mortar, OITZ and old mortar, and NITZ and new mortar were set to 2 and 10, respectively. The initial diffusion coefficients for the natural aggregate, new mortar, old mortar, NITZ, and OITZ were 0, 7.73×10^{-12} m²/s, 1.55×10^{-11} m²/s, 7.73×10^{-11} m²/s, and 1.55×10^{-10} m²/s, respectively. For comparison, the same degree of hydration (0.4), erosion time (235 d) and surface chloride concentration (0.46%) were set as in the experimental data reported by Xiao[32]. The comparison of the simulation results with the experimental results is shown in Fig 2. As can be seen from Fig. 2, the simulation results are in good agreement with the experimental results, which indicates that the finite element modelling has good reliability. Next, we will use the finite element model to investigate the effects of different factors on the diffusion of chloride ions in RAC.

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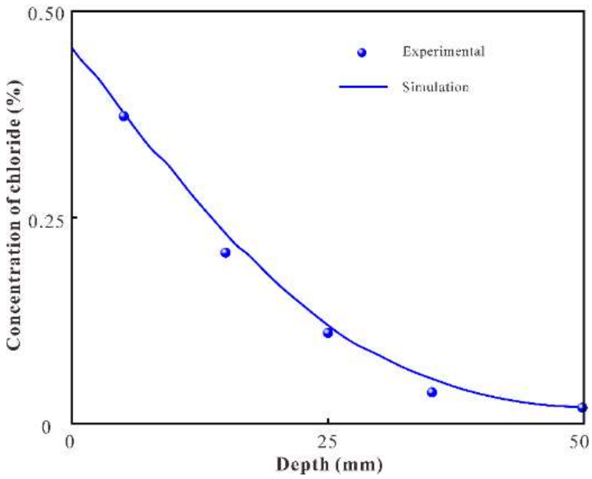

Fig. 2 Comparison of simulation results with experimental results. Experimental reproduced from Ref. 32 (reprinted with permission from ref. 32, copyright 2014 Elsevier).

3.2 Effect of Recycled Aggregate Distribution

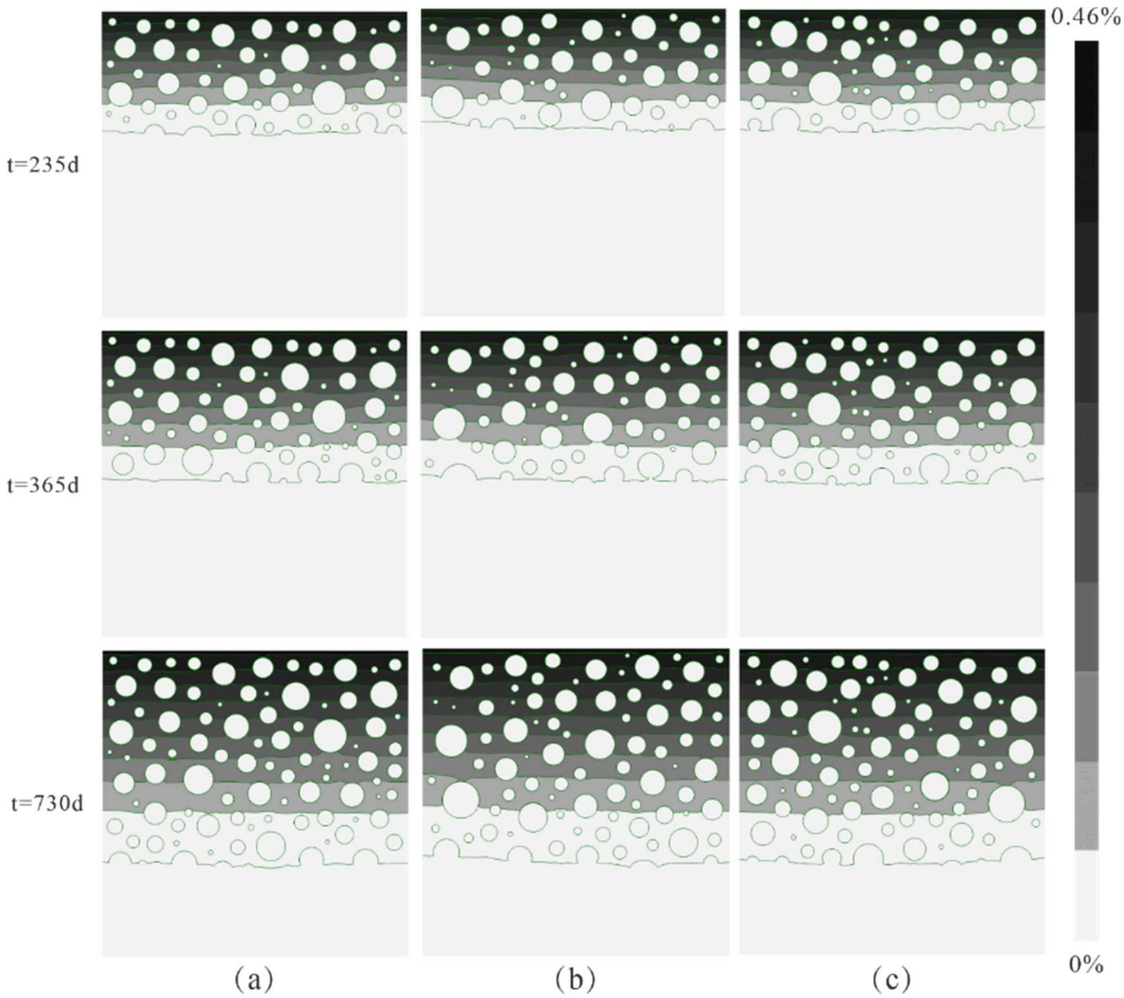

Fig. 3 Cloud plots of chloride ion concentration vs. diffusion depth in RAC with different distributions of recycled aggregates. The erosion time was set to 235d 365d and 730d, respectively. The recycled aggregates in regions with concentrations below 0.02% (t = 365 d) and 0.05% (t = 730 d) have been omitted to show the diffusion of chloride ions more clearly.

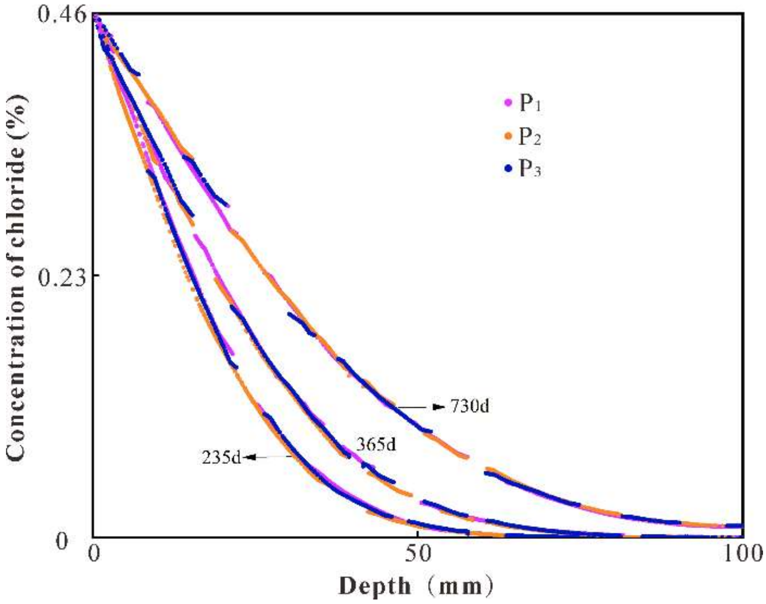

Fig. 4 Isoline concentration of chloride ions as a function of depth in RAC with different distribution of recycled aggregates. Data were collected at three locations, P_1, P_2 and P_3 shown in Fig. 1a.

The distribution of recycled aggregates may affect the diffusion of chloride ions in RAC. To investigate this effect, we constructed a mesoscopic model with random distribution of recycled aggregate using the same RAC. The erosion time was set to 235 d, 365 d, and 720 d, respectively. The cloud plots of chloride ion concentration versus diffusion depth are shown in Fig. 3. It can be seen that the diffusion of chloride ions is almost the same in RACs with different distributions of recycled aggregates. To further clarify this point, we carefully extracted isolated lines of chloride ion concentration at different depths. The results are shown in Fig. 4. As can be seen in Fig. 4, the curves with the same erosion time overlap almost completely. Both the same cloud plots and the isolines of chloride ion concentration indicate that the distribution of recycled aggregates has little effect on the diffusion behavior of chloride ions in RAC. These results indicate that the mesoscale model is reliable and can be used to describe RAC.

3.3 Effect of Fine Structures

The fine structure in the RAC also affects the diffusion behavior of chloride ions in different ways. In order to clarify the effect of the fine structure, the RAC model was constructed in three ways: (a) a homogeneous phase consisting of mortar; (b) a three-phase consisting of natural aggregate, ITZ and mortar; and (c) a five-phase consisting of natural aggregate, OITZ, old mortar, NITZ and new mortar. The erosion time was set to 235 d. The diffusion coefficients for each phase were set as described in section 2.3. A critical concentration of 0.1% was introduced to determine the diffusion of chloride ions. Areas with concentrations above 0.1% are shown in red and other areas are shown in white. The results are shown in Figs. 5a-c. Three features can be found from Figs. 5a-c: 1) the critical line of the single-phase model is a straight line, while the critical lines of the other two models are discontinuous; 2) the five-phase model has the largest diffusion depth, followed by the three-phase model, and lastly, the single-phase model; 3) the chloride ions are present in the interfacial transition zone and in the old mortar. The discontinuity of the critical line in the three-phase and five-phase models can be attributed to the zigzag effect and the dilution effect of the aggregates. The same zigzag effect was observed in the Zhang[33] and Wu[34].The presence of chloride ions in the interfacial transition zone and in the old mortar suggests that their influence on the diffusion of chloride ions cannot be ignored. Testing the chloride ion concentration at the foremost edge in experiments is a great challenge, however, numerical simulations have advantages in addressing this issue.

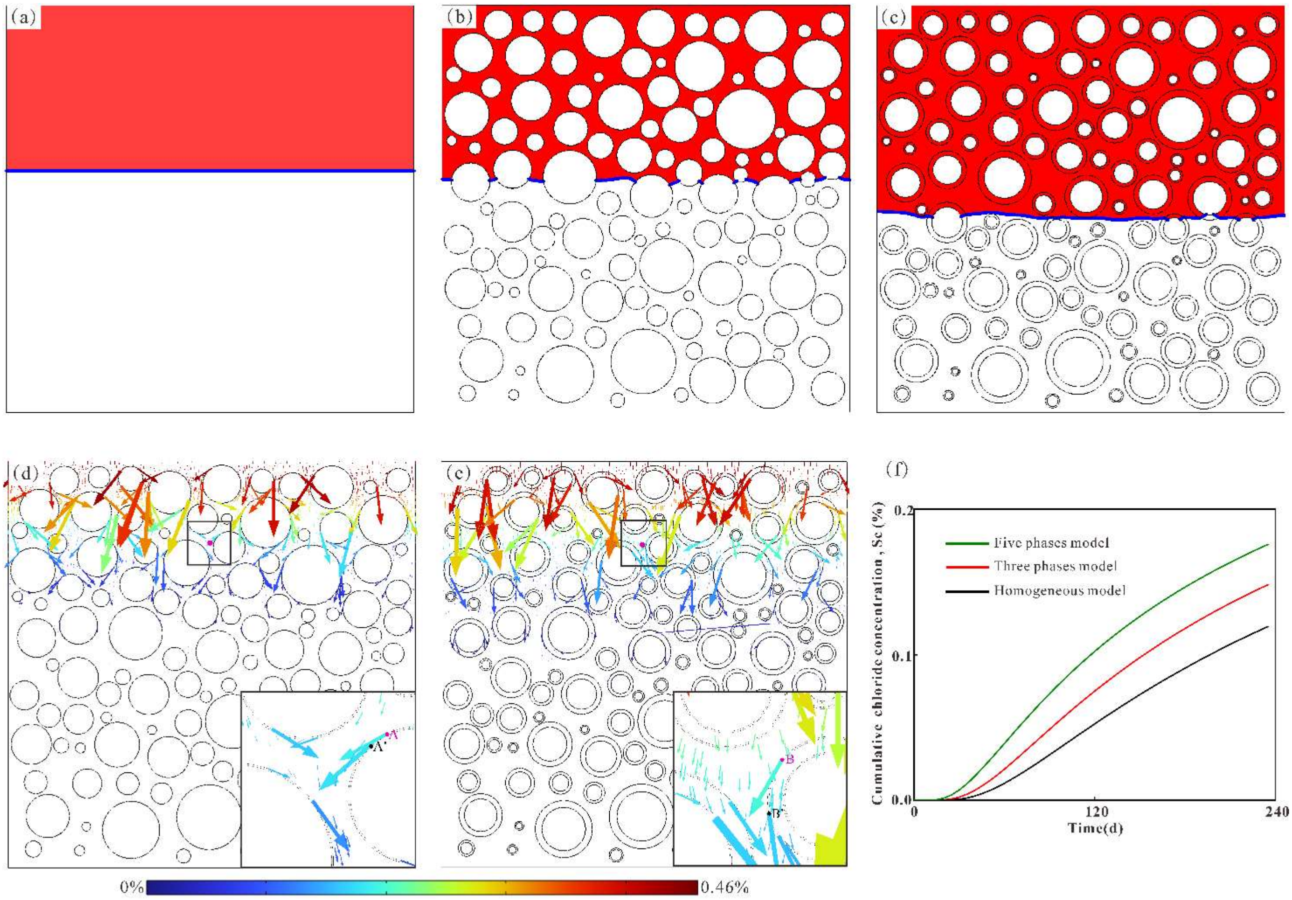

Fig. 5 (a-c) Distribution of chloride ions in the RAC models constructed for (a) homogeneous mortar, (b) three phases including natural aggregate, ITZ and mortar, and (c) five-phases including natural aggregate, OITZ, old mortar, NITZ and new mortar. The blue lines in (a-c) represent the locations where the critical concentration is 0.1 %. (d-e) Migration clouds of chloride ions in the RAC consisting of (d) three phases and (e) five phases. The insets in (d) and (e) are magnified views of the square region. The direction, color and the length of the arrows represent the migration direction, concentration and concentration gradient of chloride ions, respectively.

In order to clarify the diffusion behavior of chloride ions in the three-phase and five-phase models, the migration cloud plots of chloride ions are shown in Figs. 5d and e, respectively. The insets in Figs. 5d and e are enlarged view of zones highlight with black boxes. Here, the migration cloud plots are represented by arrows whose direction, color and length represent the direction, the concentration and concentration gradient of chloride ions. It can be seen that the larger concentration gradient is mainly distributed around the aggregates. As for the chloride ions around the aggregates, their diffusion directions are not parallel due to the impermeability of the aggregate (see the arrows at points A and A' in Fig. 5d). In addition, more chloride ions appear in the area consisting of old mortar (see Fig. 5e), suggesting that the presence of old mortar accelerates the diffusion of chloride ions. In order to show the difference quantitatively, the cumulative concentration of chloride ions at position (50, 80) was shown in Fig. 5f. It can be seen that the cumulative concentrations in the five-phase model are always higher than those in the three-phase and single-phase models. As an example, for the case of erosion time of 235 day, the cumulative chloride ion concentration increased by 24% and 47% for the three-phase and five-phase models, respectively, compared to the single-phase model. These results clearly show that chloride ions are more easily transported in the RAC due to the presence of old mortar and OITZ.

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3.4 Effect of Old Mortar

The main difference between natural aggregate cement and RAC is that recycled aggregate has a layer of old mortar on its surface. The content of OM is reported to be 30%-65% of the recycled aggregates. Here, the content of recycled aggregates and old mortar are set at 50% and 40%, respectively. In practice, the sources of recycled aggregates vary considerably, which may also result in different diffusion coefficients. For example, Xiao [19] reported that the diffusion coefficients for old mortar is 1-5 times higher than that of new mortar. In order to investigate the effect of old mortar, the ratio of diffusion coefficients (R_{D1}) of old mortar and new mortar were set to 2, 3, 4 and 5, respectively, and the erosion time were set to 365 d and 730 d, respectively. The cloud plots of chloride ions are shown in Fig. 6. It can be seen that the diffusion depth increases slightly with increasing R_{D1} (see panels with the same erosion time). For RACs with the same R_{D1}, the increase in diffusion depth is more pronounced with increasing erosion time.

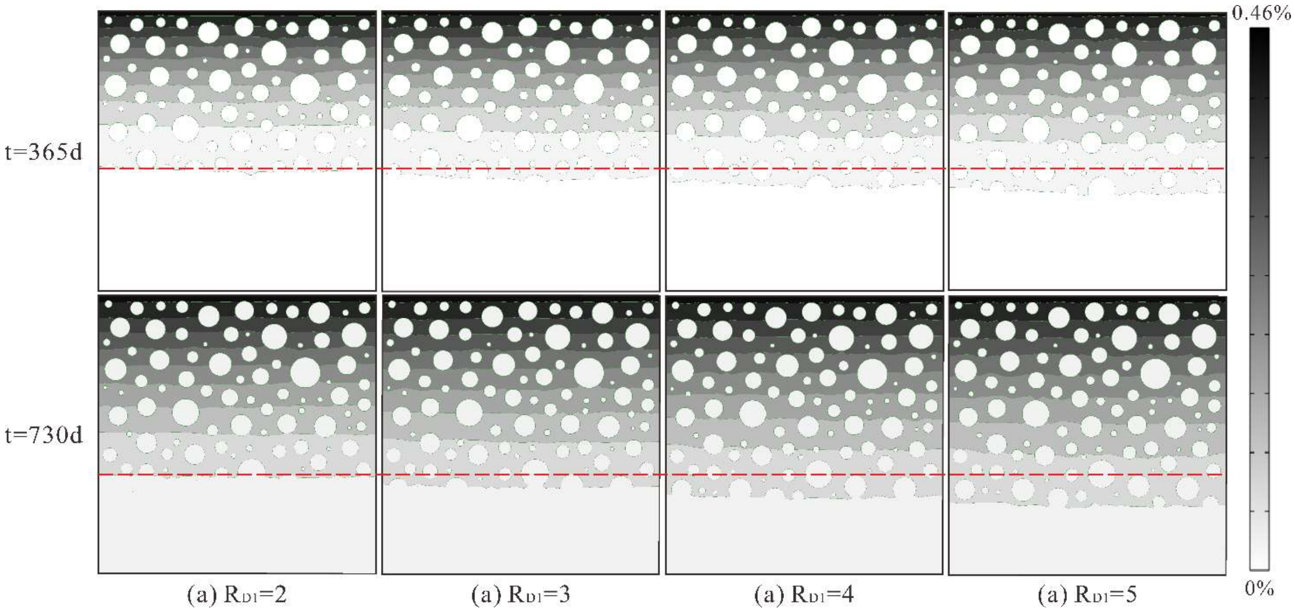

Fig. 6 Cloud plots of chloride ions with different R_{D1} and erosion time. The recycled aggregates in regions with concentrations below 0.02% (t = 365 d) and 0.05% (t = 730 d) have been omitted to show the diffusion of chloride ions more clearly. The red dashed line represents the depth of the forefront of the RAC with R_{D1} = 2.

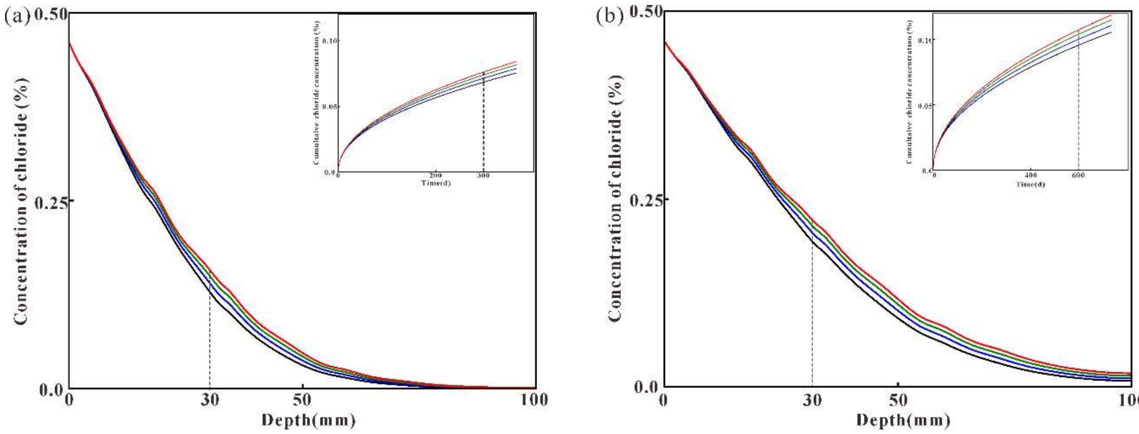

Fig. 7 Chloride ion concentration as function of diffusion depth for erosion time of (a) 365 d and (b) 730 d. The cumulative chloride concentrations as function of erosion time are shown as insets. Black, blue, green and red colors represent recycled aggregates with R_{D1} of 2, 3, 4, and 5, respectively.

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In order to show more clearly the effect of the old mortar on the diffusion of chloride ions, the chloride ion concentration at different depths is shown in Fig. 7. As can be seen in Fig. 7, the slope of the curve of chloride ion concentration versus depth increases with increasing R_{D1}, which indicates that the migration rate increases with increasing R_{D1}. This effect can also be observed from the cumulative chloride concentration versus erosion time (see the inset of Fig. 7). It can be seen that the cumulative chloride concentration increases with increasing R_{D1}. For example, at an erosion time of 300 d, the cumulative concentrations in the RACs are 0.069%, 0.072%, 0.074% and 0.076% when R_{D1} increases from 2 to 5. For RACs with an erosion time of 600 d, the cumulative chloride concentrations are 0.096%, 0.10%, 0.104% and 0.107% when R_{D1} increases from 2 to 5. The results indicate that old mortar with a larger porosity is less resistant to chloride ions. This result is in agreement with the findings of Hu and co-workers. [23]

3.5 Effect of OITZ

The interfacial transition zone is susceptible to chloride ion attack due to its high porosity compared to the mortar matrix. Therefore, it is crucial to study the effect of OITZ. The diffusion coefficients of NITZ are reported to be 1.3 to16.2 times higher than those of new mortar. Here, in order to study the effect of OITZ, the relative ratio of diffusion coefficient R_{D2} (defined as the ratio of diffusion coefficient of OITZ to that of old mortar) was set to 4, 8, 12 and 16, and the erosion time was set to 365 d and 730 d, respectively. The cloud plots of chloride ions were shown in Fig. 8. As shown in Fig. 8, it can be seen that the diffusion depth increases with the increase of R_{D2} and erosion time. In order to show the diffusion more clearly, the concentration change along the transition direction is shown in Fig. 9. It can be seen that for the same depth, the concentration of chloride ions in the RAC is always greater for larger R_{D2}. A similar variation is observed for the cumulative concentration. For a fixed erosion time, the cumulative concentration increases with increasing R_{D2}. For example, for an erosion time of 600 d, the cumulative concentrations are 0.096%, 0.10% ,0.104%, and 0.107% for R_{D2} equals to 4, 8, 12, and 16, respectively. The diffusion of chloride ions in the OITZ is mainly attributed to the high porosity structure caused by the adhered old mortar [35, 36]. Therefore, it is recommended to remove the old mortar around the recycled aggregate to improve the durability of RAC.

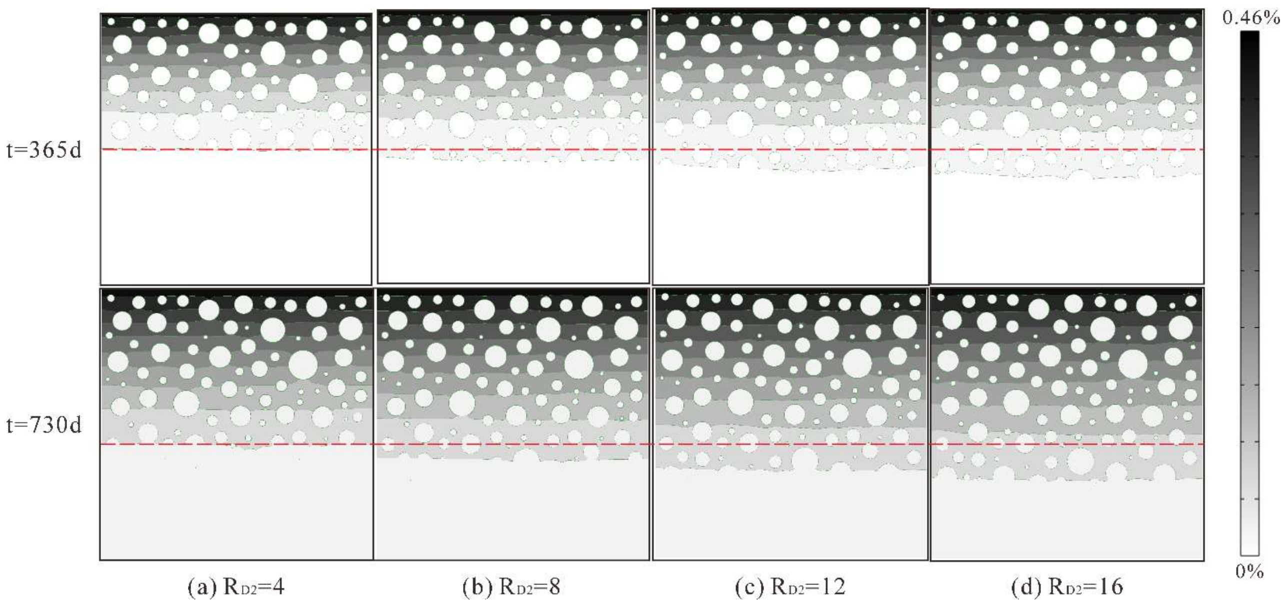

Fig. 8 Cloud plots of chloride ions with different R_{D2} and erosion time. The recycled aggregates in regions with concentrations below 0.02% (t = 365 d) and 0.05% (t = 730 d) have been omitted to show the diffusion of chloride ions more clearly. The red dashed line represents the depth of the forefront of the RAC with R_{D2} = 4.

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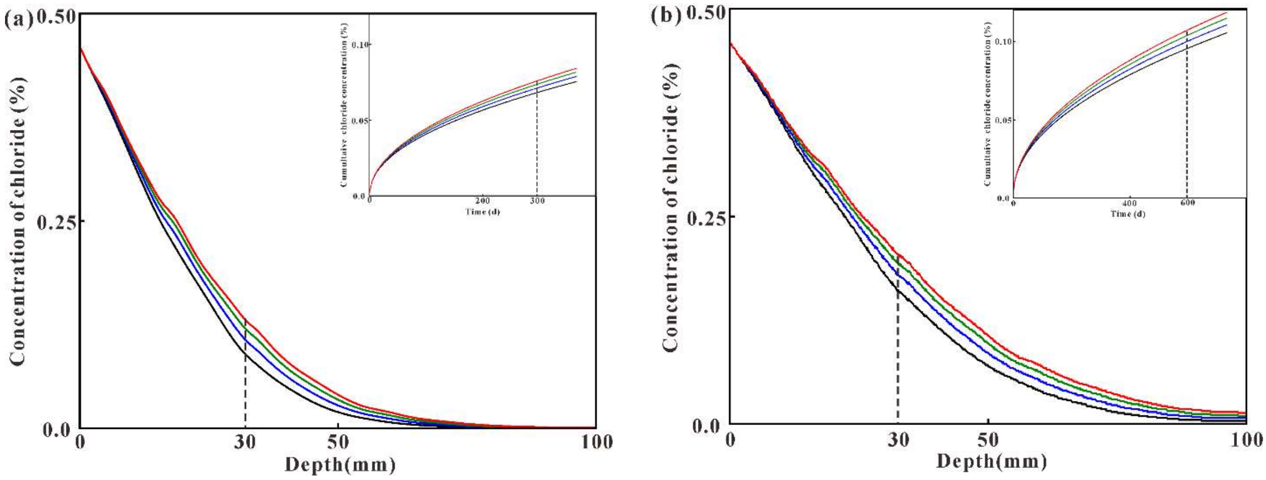

Fig. 9 Chloride ion concentration as function of diffusion depth for erosion time of (a) 365 d and (b) 730 d. The cumulative chloride concentrations as function of erosion time are shown as insets. Black, blue, green and red colors represent recycled aggregates with R_{D2} of 4, 8, 12, and 16, respectively.

3.6 Effect of Ratio of Water to Cement

The water-cement ratio (w/c) in cement ranges from 0.3 to 0.6 [20, 37-39]. It determines the degree of hydration of the cement, which in turn affects its durability. In order to assess the effect of the water-cement ratio, w/c was set to 0.3, 0.4, 0.5 and 0.6, respectively. The erosion time was set to 365 d. The cloud plots of chloride ions in RACs with different water-cement ratios are shown in Fig. 10. The results show that the depth of diffusion increases with the water-cement ratio, which suggests that chloride ions diffuse more rapidly in RACs with higher water-cement ratios. In order to assess this effect more quantitatively, chloride ion concentrations at different diffusion depths and cumulative concentrations at different erosion time were also collected. The results are shown in Fig. 11. It can be seen that the chloride concentration in the RAC increases with increasing water to cement ratio at the same diffusion depth (see Fig. 11a). For example, at a depth of 30 mm, the concentrations are 0.043%, 0.128%, 0.192%, and 0.235% for water-cement ratios of 0.3, 0.4, 0.5 and 0.6, respectively, and the cumulative concentrations are 0.045%, 0.069%, 0.091%, and 0.111% for ratios of 0.3, 0.4, 0.5, and 0.6, respectively, at an erosion time of 300 d. The changes in concentration and cumulative concentration further indicate that chloride ions diffuse more rapidly in RACs with higher w/c. While lower w/c can be effective in improving resistance to chloride attack, it can also lead to high engineering costs and other problems such as poor strength, Insufficient liquidity, and Poor stability [20, 37-41]. An optimum should be found to construct RACs with good mechanical properties and excellent resistance to chloride attack.

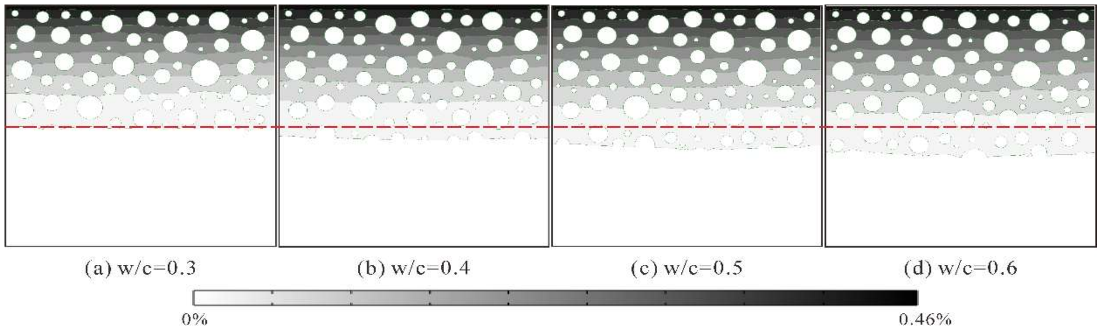

Fig. 10 Cloud plots of chloride ions in RAC with different water-cement ratios. The recycled aggregates in regions with concentrations below 0.02% have been omitted to show the diffusion of chloride ions more clearly. The red dashed line represents the depth of the forefront of the RAC with w/c = 0.3.

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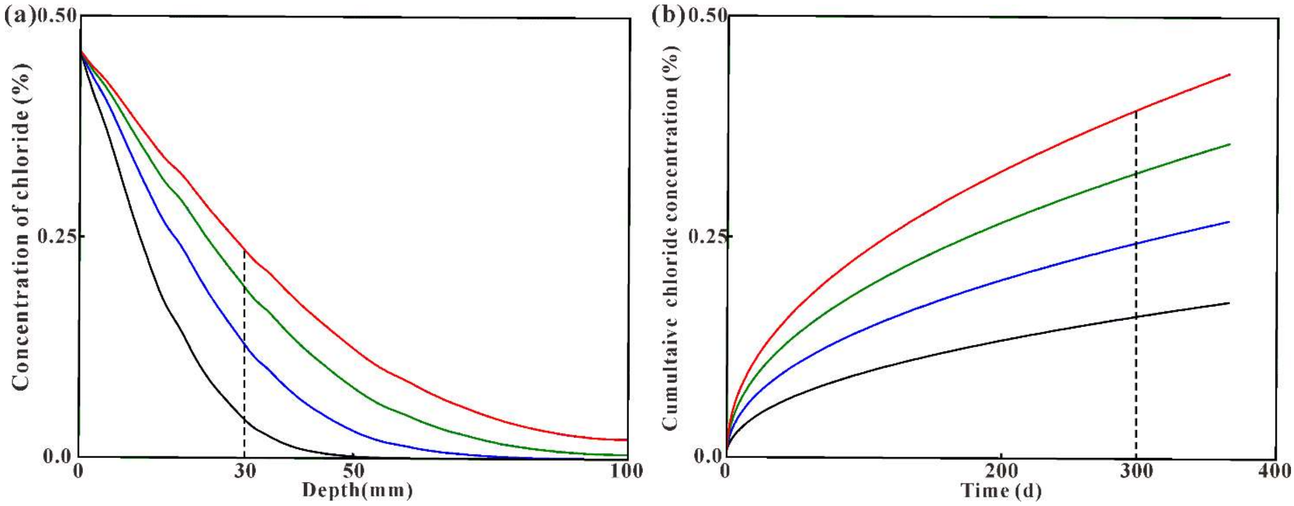

Fig. 11 (a) Chloride ion concentration as function of diffusion depth for erosion time of 365 d. (b) The cumulative chloride concentrations as function of erosion time. Black, blue, green and red colors represent RAC with w/c equals to 0.3, 0.4, 0.5, and 0.6, respectively.

4. Conclusion

In this paper, a five-phase mesoscopic model of RAC was established based on the finite element method, and the influencing factors of the diffusion of chloride ions in RAC were systematically studied using this model. The following results can be obtained:

(1) The distribution of recycled aggregate has little influence on the diffusion of chloride ions in RAC.

(2) The diffusion trajectories of chloride ions in RAC indicate that the fine structure of RAC has an influence on the diffusion of chloride ions. Chloride ions diffuse the most in the five-phase RAC model, followed by the three-phase model and then the single-phase model.

(3) It is essential to determine the exact ratio of the old to new mortar and the old interfacial transition zone to the new interfacial transition zone, as they directly affect the transition of chloride ions.

(4) As the water to cement ratio increases, the diffusion of chloride ions also increases significantly. It is very important to choose appropriate w/c ratio to obtain RAC with good mechanical properties and resistance to chloride ion attack.

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