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Influence of cracks on chloride diffusivity in concrete: a five-phase mesoscale model approach

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Abstract: This paper presents a mesoscale numerical approach to investigate the chloride diffusivity in cracked concrete. Concrete is treated as a five-phase material, including cement paste, aggregate, interfacial transition zone (ITZ), crack, and damaged zone (DZ), for its heterogeneity. In the mesoscale model, the randomly distributed aggregates were treated as impermeable, whereas all other phases are assumed permeable but with different diffusion coefficients. It is assumed that the crack is located in the middle of the DZ, and there is a liner relationship of the chloride diffusion coefficients between the DZ and the crack. The developed mesoscale model is validated by comparing the simulation results with the experimental data. Finally, the influence of the DZ, such as the chloride diffusion coefficient, the width and length of the DZ, the width and length of the crack, on the penetration of chlorides in cracked concrete is examined and discussed.

Keywords: Concrete, Crack, Chloride diffusion, Mesoscale model, Numerical simulation, Multi-phase

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1. Introduction

Corrosion of reinforcing bars caused by chloride ions is a major cause of reducing or shortening the service life of reinforced concrete (RC) structures[1-6]. Corroded RC structures are easy to be cracked by the effect of the loading. Cracks provide easy paths for chloride ions penetration in concrete. In recent years, efforts were made to investigate the influence of cracks on chloride diffusivity in cracked concrete. Rodriguez and Hooton [7] conducted an experiment of chloride diffusion in specimens with parallel-wall cracks with widths ranging from 0.10 to 0.68 mm. Win et al. [8] conducted an experimental study on chloride diffusion in cracked reinforced beams exposed to NaCl solution and found that when the water-to-cement ratio is 0.45 and 0.65, there is no significant difference between the chloride ion penetration depth from the surface of the cracked concrete and that from the exposed surface in specimens. Jang et al. [9] reported that chloride diffusion coefficient of the crack will not increase when its width reached to the “ threshold crack width ” which is found to be around 55-80 μm. Li et al. [10] investigated chloride ion transport in cracked concrete specimens with crack widths of 0.05 mm, 0.08 mm, 0.1 mm and 0.2 mm by using the rapid chloride migration (RCM) test. In their experiment, they found that the accelerated chloride migration takes place at the crack width ranging from 0.08 mm to 0.1 mm. When the crack width is less than 0.05 mm, the influence of the cracks is ignorable, and when the crack width exceeds 0.1 mm, the chloride transport is similar to that in liquid. Ismail et al. [11] conducted an experimental study on five cracked specimens which were exposed to a chloride solution for 10 hours with the crack width in the range of 21 to 128 μm. They found that there was an impediment of the capacity of chloride diffusion in the crack when its width was less than 53 μm. Further, Ismail et al. [12] found from a test of chloride diffusion in cracks with width ranging from 6 to 325 μm that cracks with width of 30 μm or less have no significant effect on chloride diffusion. These works can help us to realize the influence of cracks on chloride diffusivity in cracked concrete. However, it should be noted that the above-mentioned conclusions are not generalizable, since a lot of other factors which will also affect the chloride diffusivity in cracked concrete, such as cement types, the crack length, the crack form, etc. were not examined.

With the development of computer technology, more and more researchers focus on the use of numerical simulations to investigate chloride diffusivity in cracked concrete. This kind of simulations is efficient and requires less time than that needed in the process of the experimental study. In some works [13-16] the concrete was treated as a homogeneous material when they carried out a simulation of chloride diffusivity in cracked concrete. However, this kind of simulations, which neglect the heterogeneity of concrete, could result in inaccuracy of simulation results. Thus, recent efforts in the simulation of chloride diffusivity in cracked concrete have taken into account this influence. Wang et al. [17] proposed a 2-D mesoscale lattice model considering the mortar, aggregates and ITZ, which was validated by using the experimental data, to investigate chloride and water transport in cracked-unsaturated concrete with a single crack. They found that drying-wetting action, crack width and length within concrete are crucial for chloride transport in unsaturated cracked concrete. Du et al. [18] developed a four-phase mesoscale model consisting of the cement paste, aggregates, ITZ and cracks to study the effect of the artificial cracks and the tortuous cracks on chloride ions diffusion in cracked concrete, and found that the chloride diffusivity in cracked concrete was affected by the depth and width of the crack. Liu et al. [19] carried out a numerical study on the migration of chloride ions in cracked concrete, in which the concrete was treated as a homogeneous and heterogeneous material considering ionic interactions between different species. In their work, the damaged zone was considered to be homogenous in which the aggregate effect is deliberately not considered on the diffusion pattern of chlorides in cracked zone. Note that, the modeling of chloride diffusivity in cracked concrete should consider the effect of aggregate distribution as it can influence the chloride penetration paths, particularly in the region between the crack/damage zone and the aggregate. Generally, according to the above-mentioned studies, it can be concluded that the inhomogeneous effect of concrete on chloride diffusivity should be considered in the research on chloride diffusivity in cracked concrete. However, few studies have investigated the chloride diffusivity in cracked concrete by considering the effect of both the crack and the damage zone (DZ) around the crack at the mesoscale levels. Jones et al. (Jones, et al., 2015) proposed a two-dimensional model, which consisted of the cement paste, the DZ, and the crack, to investigate chloride diffusion in cracked concrete. However, aggregates and the ITZs were not taken into account in their study.

In this study, a five-phase mesoscale model consisting of the cement paste, aggregates, ITZs, crack, and the DZ, is developed to investigate the chloride diffusivity in cracked concrete. In the mesoscale model, the randomly distributed aggregates were treated as impermeable, whereas all other phases are assumed permeable but with different diffusion coefficients. The model is validated using experimental data. The influence of the DZ, such as the chloride diffusion coefficient of the DZ, the width and length of the DZ, and the crack, such as the width and length of the crack and the crack pattern, on the penetration of chloride ions in cracked concrete is also examined and discussed.

2. Mesoscale model of cracked concrete

In this paper, a two-dimensional mesoscale model is developed to simulate the concrete on the basis of COMSOL software, in which concrete is treated as a five-phase composite material. Each phase has an independent diffusivity property related to its micro-structure. The aggregate phase is considered as impermeable, and other four phases are treated as permeable with different diffusion coefficients. Fig.1 shows a schematic of the cracked concrete, in which the crack is modeled as an equilateral triangle within the DZ and the DZ is modeled as a rectangle shape as shown by the gray color in Fig.1. It should be noted herein that, the crack modelled in the present study has been simplified. In reality the crack would not be perfectly straight as the form of cracks will be affected by surrounding aggregates. Nevertheless, as the crack is relatively short the effect of its tortuosity on the transport of chlorides would be rather small. The dash line is for measured position and the distance between the crack and the measured position is 2 mm. The crack is assumed to be located in the middle of the damaged zone. In Fig.1, w_{cr} and w_{DZ} are the width of the crack and the DZ, respectively, and, d_{cr} and d_{DZ} are the length of the crack and the DZ, respectively. This type of the crack can be commonly found in concrete beams subjected to bending.

Fig. 1. Schematic of the cracked concrete

One of the key problems is to generate random aggregates for the mesoscale analysis. If the volume fraction and sizes of aggregates are provided, the distribution of aggregates can be obtained according to the Walraven function [20]. Fig.2 shows a typical two-dimensional mesoscale model of the cracked concrete, in which the circular areas represent aggregates with the diameter ranging from 7 mm to 20 mm and the dash line represents the measured position for chloride concentration profiles. The shapes of aggregates in real concrete are unlikely to be perfectly spherical. However, some works have demonstrated that the effect of the shape of aggregates on the chloride diffusivity in concrete is not significant [21, 22]; whereas in some cases (such as 3-D dimensions, migration process, recycled aggregates) its effect may be important [10, 23-26]. For each aggregate there is an ITZ surrounding it, and the thickness of the ITZ is assumed to be identical. As known, the ITZ has a higher porosity than the cement paste which leads to a higher chloride diffusivity [27-29]. The real thickness of the ITZ in concrete is in the range of 10-50 μm [30-33], and herein the thickness of the ITZ is set as 30 μm in the mesoscale model. Fig.3 shows the finite element meshes of the mesoscale model with triangular meshes, and the total number of meshed triangular elements is 610,724.

Fig. 2. Two-dimensional mesoscale model of the cracked concrete with dimensions of 100×100 mm

Fig. 3. Finite element meshes of the two-dimensional mesoscale model of the cracked concrete

3. Diffusion coefficient

3.1 Chloride diffusion coefficient in cement paste and ITZ

Zheng and Zhou [34] proposed an analytical solution, which was derived on the basis of the general effective medium theory, to determine chloride diffusion coefficient of the cement paste, D_{cp}, which can consider the effect of gel and capillary pores and the solid part of the cement, as

$$D_{cp}=\frac{2.14\times10^{-10}V_p^{2.75}}{V_p^{1.75}\left(3\text{-}V_p\right)+14.44\left(1\text{-}V_p\right)^{2.75}} \tag{1}$$

where V_p is the porosity of cement paste, and its expression is given by

$$V_p=\frac{w/c-0.17\alpha}{w/c+0.32} \tag{2}$$

Where w/c is the water-to-cement ratio, α denotes the degree of hydration and its expression is given by [35]

$$\alpha=1-3.15\exp\left(w/c\right) \tag{3}$$

It is worth noting that Garboczi and Bentz [36] pointed out that the w/c redistribution will take place for a high w/c of 0.5. Therefore, the w/c ratio is preferably selected to be less than 0.5 in this approach.

Pan et al. [37] studied the relationship between D_{ITZ}/D_{cp} and t_{ITZ} based on existing experimental data, and then obtained an empirical formula by fitting the data. The expression is written as

$$D_{ITZ}=D_{cp}\left(139.434/t_{ITZ}+1.0\right) \tag{4}$$

where t_{ITZ} is the thickness of the ITZ. D_{ITZ} and D_{cp} are the diffusion coefficient of ions in the ITZ and in the cement paste, respectively.

In this study, concrete is considered fully saturated and the transport of ions is driven by the gradient of the concentration, and thus Fick's second law is adopted to determine the chloride concentration

$$\frac{\partial C_k}{\partial t}-D_{k,x}\frac{\partial^2 C_k}{\partial x^2}-D_{k,y}\frac{\partial^2 C_k}{\partial y^2}=0 \tag{5}$$

where C_k is the chloride concentration, D_k is the chloride diffusion coefficient in phase k (k=1~5), namely the cement paste, aggregates, ITZs, crack, and the DZ, and $D_{,x}$ and $D_{,y}$ are the chloride diffusion coefficient in x and y directions, respectively.

3.2 Diffusion coefficient of ions in cracks

As mentioned above, the crack can significantly accelerate chloride penetration in concrete, and thus it is critical to determine the chloride diffusion coefficient of the crack in the mesoscale model. There are a lot of liner relationships between crack widths and chloride diffusion coefficients which were derived on the basis of the experimental data. In the work of [18], the relationship between the crack width and chloride diffusion coefficient was obtained by taking an average of the two equations, which were fitted to the test data of chloride diffusion into cracked ordinary concrete, respectively. However, one of the shortcomings in their work is to ignore the influence of threshold value of the crack. Hence, the expression proposed by Djerbi et al. [38] is introduced into this study, which was also employed by Šavija, et al. [39] in the lattice model of the cracked concrete, which demonstrated that the simulation results matched experimental data well. The expression is given as

$$\begin{aligned} &D_{cr} = 2\times10^{-11} w_{cr} - 4\times10^{-10} && 30\mu m \le w_{cr} \le 80\mu m \\ &D_{cr} = 14\times10^{-10} && w_{cr} \ge 80\mu m \end{aligned} \quad (6)$$

where w_{cr} in μm represents the crack width.

4. Validation of the mesoscale model

In order to verify the developed mesoscale model, experimental data published in [40], which is for concrete beams with water-to-cement ratio (w/c) of 0.485 and having the exposed time of 30 days, are utilized. In the experiment of [40], the reinforced concrete beam specimens were cracked with different widths by bending. In this study, six cracks, which are obtained from the experiment, are divided into two groups. The first group, which has three cracks with the crack width of 0 μm, 29.4 μm, and 102.9 μm, and corresponding length of 0 mm, 18.7 mm, and 36.6 mm, respectively, are used to determine the magnitude of D_{DZ}/D_{cp} (D_{DZ} is the diffusion coefficient in the damaged zone). At present, few investigations were made on the quantitative relationship of chloride diffusion coefficients in the DZ and that in the cement paste, and thus one of the key problems is to determine the magnitude of D_{DZ}/D_{cp}. In this study, the width of the DZ is assumed to be the same as 2 mm, the length of the DZ is 10 mm longer than the corresponding crack's length, and the surface chloride concentration is 0.51%. It should be pointed out that, the surface chloride concentration used in the model refers to the chloride concentration of the NaCl solution which will not change with time, and the chloride diffusion into concrete is in non-steady-state condition. Herein, three magnitudes of D_{DZ}/D_{cp} are selected as 15, 20 and 25 in the present mesoscale model to investigate which will yield in good agreement with the test data. A comparative analysis between simulation results with different magnitudes of D_{DZ}/D_{cp} and the test data is carried out, as presented in Fig.4. It is concluded that when the magnitude of D_{DZ}/D_{cp} is selected as 20, the simulation results match the experimental data well by using the statistical method. Hence, the magnitude of D_{DZ}/D_{cp} in this study is recommended to be 20, which is similar to the works of [13, 19].

Fig. 4. Comparison of simulation results and the test data with different magnitudes of the D_{DZ}/Dcp

The second group of cracks used herein, which also has three cracks with the crack width of 49 μm, 210.7 μm, and 283 μm, and corresponding length of 28.1 mm, 47.3 mm, and 63.2 mm, respectively, is to validate the developed model, as presented in Fig.5. It can be seen from Fig.5 that, in general, the simulation results can match the test data well. However, there is still a slight difference for the chloride diffusion close to the two-dimensional diffusion when the crack width is larger than 210 μm. Therefore, it can be concluded that the developed mesoscale model in this paper has a good accuracy in predicting the chloride diffusivity in cracked concrete when the crack width is less than 210 μm, and there are some works needed to investigate the influence of large cracks on chloride diffusion in cracked concrete.

Fig. 5. Comparison of the simulation results and the test data of [40]

Fig. 6. Comparison of the simulation results and the test data of [41]

Moreover, ZHANG et al. [41] carried out an experiment to investigate the influence of cracks on chloride diffusivity, in which the w/c ratio is 0.6 and each specimen only contains a parallel crack. The surface chloride concentration is 5% (by weight of cement), and the time of exposure is 30 days. In this paper, the group B test data is selected to validate the proposed model, in which the crack width is 0.2 mm and 0.3 mm, but the crack length is the same, both are 100 mm. Fig. 6 shows the comparison of the simulation results and the test data. It can be indicated from Fig. 6 that, when the penetration depth is deeper than 10 mm, the simulation results are in good agreement with the test data. In addition, it is noted from Fig. 5 and Fig. 6 that, in order to obtain more accurately simulated results, it is crucial to determine the real chloride diffusion coefficient when the crack width is larger than 200 μm. Overall, the five-phase mesoscale model proposed in this study can be used to predict chloride diffusivity in cracked concrete with good accuracy.

5. Analysis with/without considering the influence of the DZ

To obtain a better understanding of the influence of the DZ on chloride diffusivity in cracked concrete, a sensitivity analysis is carried out. In the analysis, the crack width, length, and the time of exposure are taken as 100 μm, 30 mm, and 365 days, respectively; whereas the width and length of the DZ are taken as 2 mm and 40 mm, respectively. Chloride concentration distributions at 365 days of exposure obtained from the present mesoscale model with and without considering the influence of the DZ are shown in Fig.7. It can be noted from Fig.7 that the crack has a significant influence on the chloride diffusivity in cracked concrete, and the chloride penetration depth with considering the influence of the DZ is much deeper than that without considering it. A comparison of chloride concentration profiles between the mesoscale models with considering the influence of the DZ and that without considering it is performed, as presented in Fig.8. It can be seen from Fig.8 that the DZ has a significant influence on chloride diffusivity in cracked concrete for it can accelerate chloride penetration in concrete. This is because the chloride concentration calculated by the mesoscale model with considering the influence of the DZ is much higher than that without considering it, and the reason for this is that the DZ has higher porosity when compared with the cement paste. In addition, one can obviously see from Fig.8 that the chloride concentration profile in the region near the top of the damaged zone varies evidently, indicating that the length of the DZ is a turning point of the chloride concentration profile along the depth.

Fig. 7. Chloride concentration distributions without / with considering influence of the DZ

Fig. 8. Comparisons of chloride concentration profiles between the mesoscale models

with / without considering the DZ

As mentioned above, the DZ has a pronounced influence on chloride diffusivity in cracked concrete, and in order to effectively distinguish this influence, three magnitudes of D_{DZ}/D_{cp}, i.e., 10, 20 and 30, are selected to investigate the influence of the D_{DZ} on chloride diffusivity in cracked concrete, as presented in Fig.9. It can be seen from Fig.9 that the larger the value of the D_{DZ}, the deeper the penetration depth. Fig.10 shows a comparison of chloride concentration profiles between different models with different values of the D_{DZ}. In Fig.10, it can be seen that different magnitudes of the D_{DZ}/D_{cp} lead to significant difference in chloride concentration, especially in the region from the surface to the length of the DZ, the difference between the profiles of the chloride concentration increases gradually. However, when the penetrated depth exceeds the length of the DZ, the difference narrows.

Fig. 9. Chloride concentration distributions with different magnitudes of DZ

Fig. 10. Comparisons of chloride concentration profiles between different models with different values of D_{DZ}

The influence of geometric parameters of the damaged zone, i.e., the width and length of the DZ, on chloride diffusivity in cracked concrete is also examined numerically herein. First, three lengths of the DZ, i.e., 30 mm, 35 mm, and 40 mm, are accounted for in the mesoscale model, but the width of the DZ is assumed to be the same as 2 mm. Fig.11 shows the chloride concentration distributions simulated by using the mesoscale model with different lengths of the DZ. It can be obviously seen from Fig.11 that the chloride penetration depth increases with the increase of the length of the DZ. In order to clearly reveal the difference of chloride concentrations between the mesoscale models, a comparison of chloride concentration profiles between three models with different lengths of the DZ are shown in Fig.12. It can be seen from Fig.12 that there is an intersection between the chloride concentration profiles. When the penetration depth is less than the depth of the intersection, the shorter the length of the DZ, the higher the chloride concentration. The reason for this is that chloride diffusion rate is markedly influenced by the length of the DZ. When the region is close to the surface, owing to the different chloride diffusion rate, the chloride concentration in the region with shorter length DZ is higher than that with higher length DZ. However, when the penetration depth is deeper than the length of the intersection, the situation becomes opposite. This is because the penetration depth of chlorides is positively related to the length of the DZ.

Fig. 11. Chloride concentration distributions with different lengths of the damaged zone

Fig. 12. Comparisons of chloride concentration profiles between three models (different lengths of the DZ)

Similarly, three widths of the DZ, i.e., 1.5 mm, 2.0 mm, and 3.0 mm, are selected in the mesoscale model to investigate its influence on chloride diffusivity in cracked concrete. Fig.13 shows the chloride concentration distributions simulated by mesoscale models with different widths of the DZ, in which the length of the DZ is kept as a constant (40 mm). It can be seen from Fig.13 that the chloride penetration depth increases with the increase of the width of the DZ. Also, a comparison of chloride concentration profiles between three models with different widths of the DZ is presented in Fig.14, showing that the width of the DZ has a pronounced influence on chloride diffusivity in cracked concrete.

Fig. 13. Chloride concentration distributions with different widths of the damaged zone

Fig. 14. Comparisons of chloride concentration profiles between three models (different widths of the DZ)

As a result, either the width or the length of DZ is not a negligible influencing factor in the mesoscale analysis for chloride diffusivity in cracked concrete. Therefore, how to accurately determine the width, length, and the area of the DZ is an important and meaningful work in the future.

6. Parametric analysis

6.1 Influence of crack width

To investigate the influence of the width of cracks on chloride diffusivity in cracked concrete, five crack widths of 30, 50, 70, 100, and 300 μm, are utilized; while the crack length remains unchanged (30 mm) in the simulations. The width and length of the damaged zone are set as 2 mm and 40 mm, respectively. Note that, in general, the larger width of the crack leads to the larger length, that is to say, the crack length should also change when the crack width varies. However, as this is a parametric study it is more convenient to investigate each individual parameter separately. In the mesoscale model, the surface chloride concentration is 0.50% and the time of exposure is 365 days. Fig.15 shows the chloride concentration distributions calculated by the models with different crack widths. Fig.16 shows the comparisons of chloride concentration profiles along the depth between different models. It can be seen from Fig 16 that the width of the crack has a significant influence on chloride diffusion in cracked concrete, and the bigger difference takes place at the region from the surface to the length of the DZ.

Fig. 15. Chloride concentration distributions with different widths of the crack

Fig. 16. Comparisons of chloride concentration profiles between different models (different widths of the crack)

6.2 Influence of the crack length

Similar to the crack width, three crack lengths, i.e.,10 mm, 20 mm, and 30 mm, were selected in this section to investigate the influence of the crack length on chloride diffusivity in cracked concrete, while the crack width is kept unchanged (100 μm). The width of the DZ is set as 2 mm, and the length of the DZ is assumed to be 10 mm longer than the length of the corresponding crack. In the mesoscale model, the surface chloride concentration and days of exposure is 0.50% and 365 days, respectively. Fig.17 shows the chloride concentration distributions calculated by models with different lengths of the crack. Fig.18 shows the comparisons of chloride concentration profiles along the depth between different models, and it can be seen from Fig. 18 that the influence of the crack length on chloride diffusivity in cracked concrete is significant. Similar to the above study of influence of the length of the DZ on chloride diffusivity, there is an intersection between the chloride concentration profiles. When the penetration depth is deeper than the length of the intersection, the longer the length of the crack, the higher the chloride concentration in front of the DZ. However, when the penetration depth is less than the depth of the intersection, the shorter the length of the crack, the higher the chloride concentration. The reason for this is similar to the aforementioned analysis of the influence of the DZ, but owing to the influence of the crack, the profiles of chloride concentration change significantly when compared with that shown in Fig. 14.

Fig. 17. Chloride concentration distributions with different crack lengths

Fig. 18. Comparison of chloride concentration profiles between different models (different crack lengths)

As a result, it can be concluded that both the crack width and length can influence the chloride diffusivity in cracked concrete. If there is a crack and there is a DZ around it, when the influence of the crack is considered in the mesoscale model, the influence of the DZ should be also taken into account.

6.3 Influence of the crack pattern

In the above study, it can be found that the type of crack is considered to be tapered crack. However, in reality the form of cracks could vary. To investigate the influence of the form of the crack on chloride diffusivity, three forms of the cracks, i.e., tapered, tortuous and parallel-wall are taken into account. Whereas the length and width of cracks are kept the same for the three different crack types used in the mesoscale model. Note that the tortuous crack is connected by straight lines, and there are two turning points in the middle of the crack. The surface chloride concentration is 0.5% and the time of exposure is 365 days. Fig. 19 shows the chloride concentration distributions with different forms of the cracks. Fig 20 shows a comparison of chloride concentration profiles between different models. It can be noted from Fig 20 that the crack shape can affect the chloride diffusivity in cracked concrete. Moreover, the chloride concentration calculated by Parallel-wall crack is higher that calculated by the tapered and tortuous crack, respectively. Specifically, it can be concluded that the biggest influence on chloride diffusion is the tapered crack, the second is the tortuous crack, and the smallest is the parallel-wall crack.

Fig. 19. Chloride concentration distributions with different forms of the crack

Fig. 20. Comparison of chloride concentration profiles between different models (different crack patterns)

7. Conclusions

By treating concrete as a five-phase material, i.e., the cement paste, aggregates, ITZs, crack, and damage zone, the mesoscale model with consideration of the influence of the heterogeneous concrete has been developed to investigate chloride ions diffusion in cracked concrete. In the mesoscale model, the randomly distributed aggregates were considered impermeable, whereas the other four phases were treated as permeable materials but with different chloride diffusion coefficients. It was assumed that the crack was located in the middle of the DZ and the relationship of the chloride diffusion coefficient in the crack and the crack width in the DZ is liner. The influences of the chloride diffusion coefficient in DZ, the width and length of the DZ, the crack width and length, and the crack pattern on the chloride penetration in cracked concrete have been examined numerically. The following conclusions can be drawn from the obtained simulation results.

(1) The magnitude of D_{DZ}/D_{cp} is recommended to be 20 in the mesoscale model in which the simulation results were in good agreement with the experimental data for the chloride diffusion process is a steady state.

(2) The influence of the DZ cannot be ignored in the mesoscale analysis for chloride diffusivity in cracked concrete, and the chloride concentration profiles changed sharply at the length of DZ.

(3) The shape of the crack can affect the chloride diffusivity in cracked concrete, however the difference of the chloride concentration profiles between the tortuous and the parallel-wall crack is not significant.

(4) Both the extent of the DZ and the diffusion coefficient in the DZ are the important parameters in the present five-phase model. Therefore, experimental studies are required to determine the extent of the DZ around the crack, and to obtain a quantitative relationship between the diffusion coefficient of the DZ and that of the cement paste.

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List of Figures

Fig. 19 Chloride concentration distributions with different forms of the crack

Fig.20 Comparison of chloride concentration profiles between different models (different crack patterns

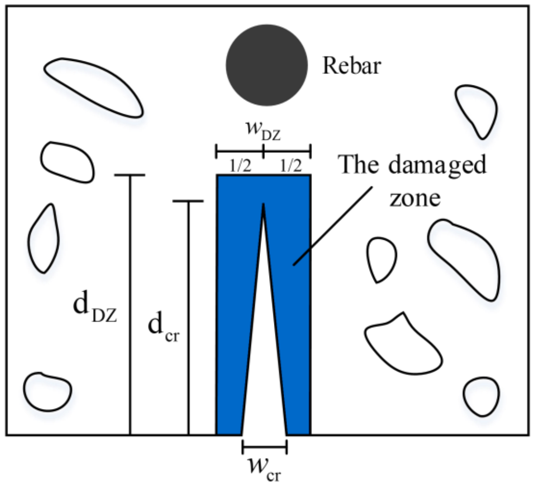


Fig. 1. Schematic of the cracked concrete

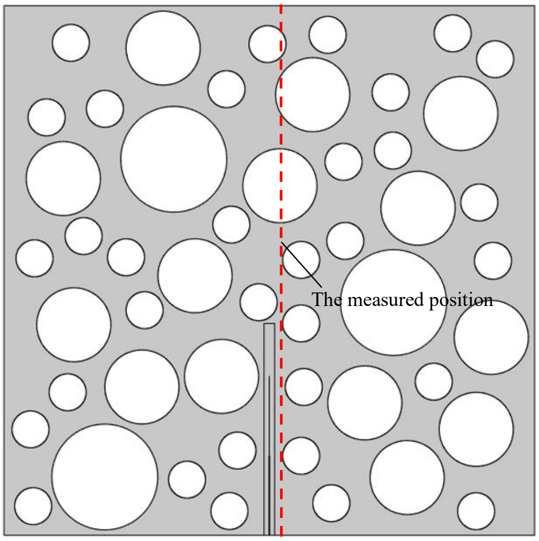


Fig. 2. Two-dimensional mesoscale model of the cracked concrete with dimensions of 100×100 mm

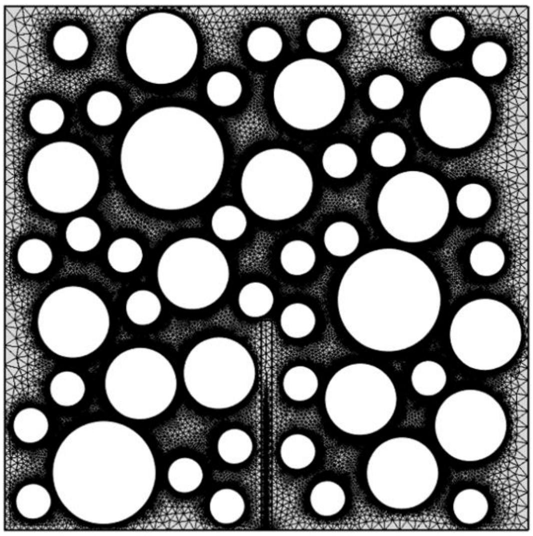
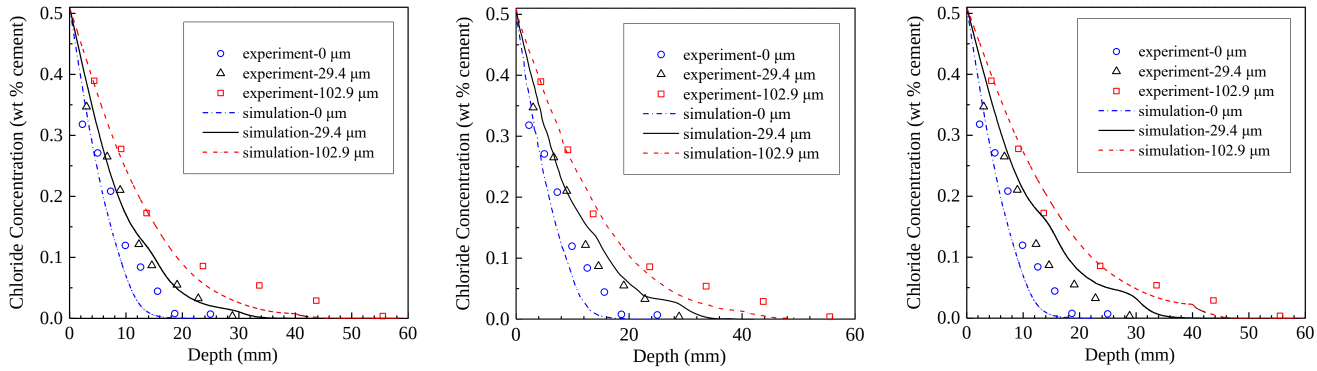


Fig. 3. Finite element meshes of the two-dimensional mesoscale model of the cracked concrete



(a) D_{DZ}=15Dcp (b) D_{DZ}=20Dcp (c) D_{DZ}=25Dcp

Fig. 4. Comparison of the simulation results and the test data with different magnitudes of the D_{DZ}/Dcp

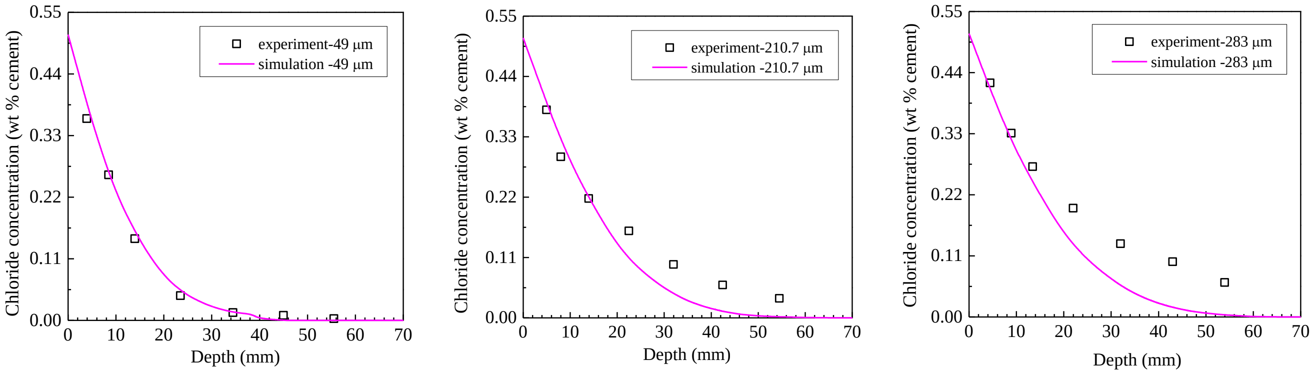


Fig. 5. Comparison of the simulation results and the test data of [40]

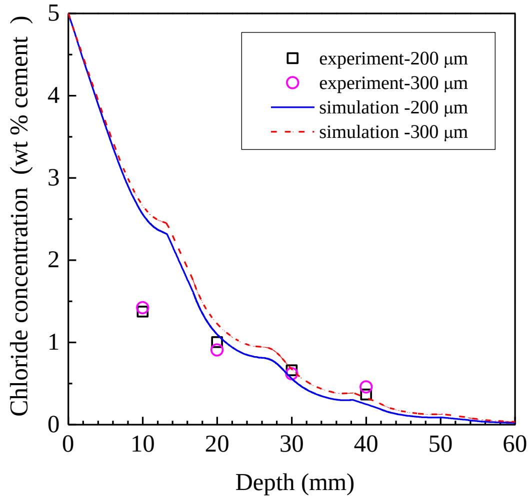
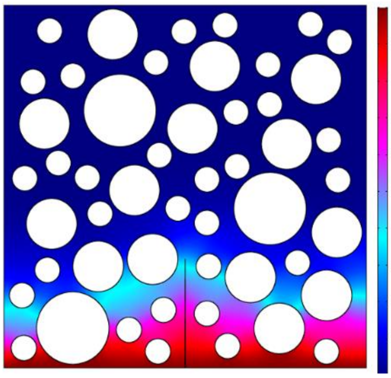
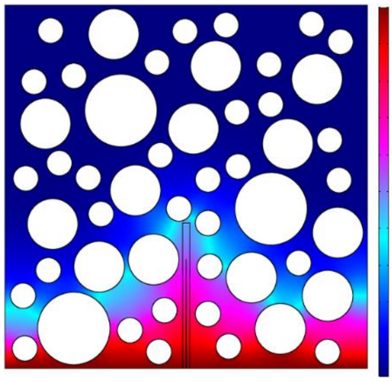


Fig. 6. Comparison of the simulation results and the test data of [41]



(a) Model without considering influence of the DZ



(b) Model with considering influence of the DZ

Fig. 7. Chloride concentration distributions without / with considering influence of the DZ

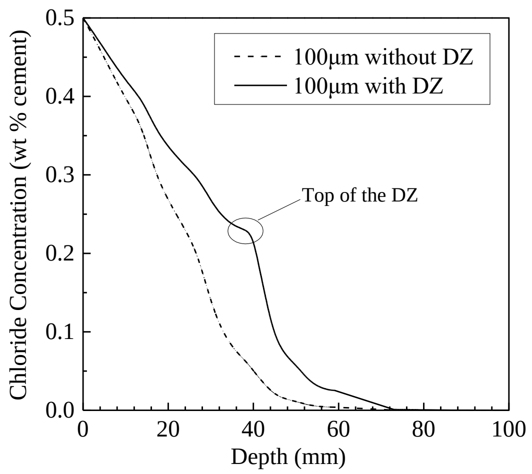
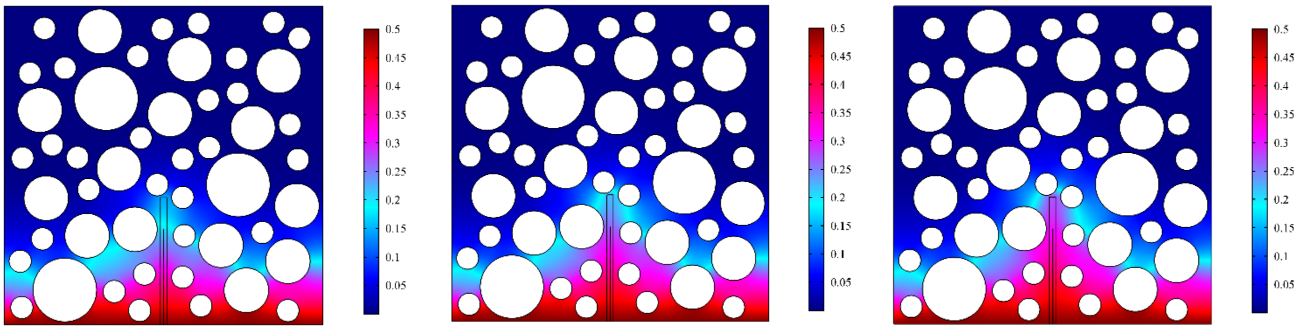


Fig. 8. Comparisons of chloride concentration profiles between the mesoscale models with / without considering of the DZ



(a) $10D_{cp}$ (b) $20D_{cp}$ (c) $30D_{cp}$

Fig. 9. Chloride concentration distributions with different magnitudes of DZ

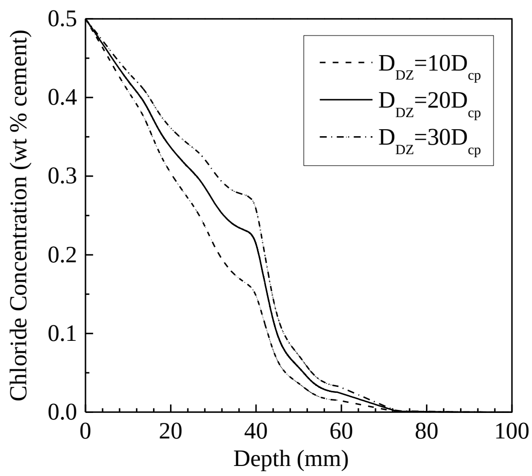
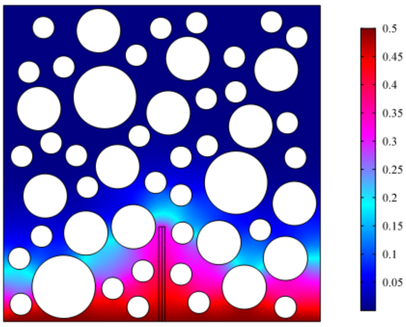
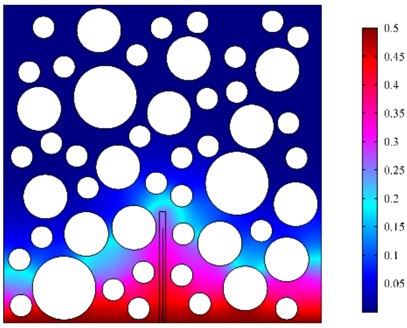


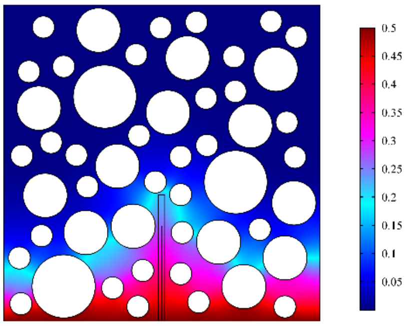
Fig. 10. Comparisons of chloride concentration profiles between different models with different values of D_{DZ}



(a) 30 mm



(b) 35 mm



(c) 40 mm

Fig. 11. Chloride concentration distributions with different lengths of the damaged zone

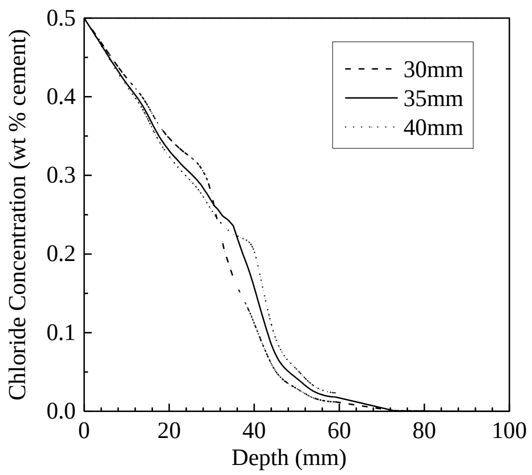
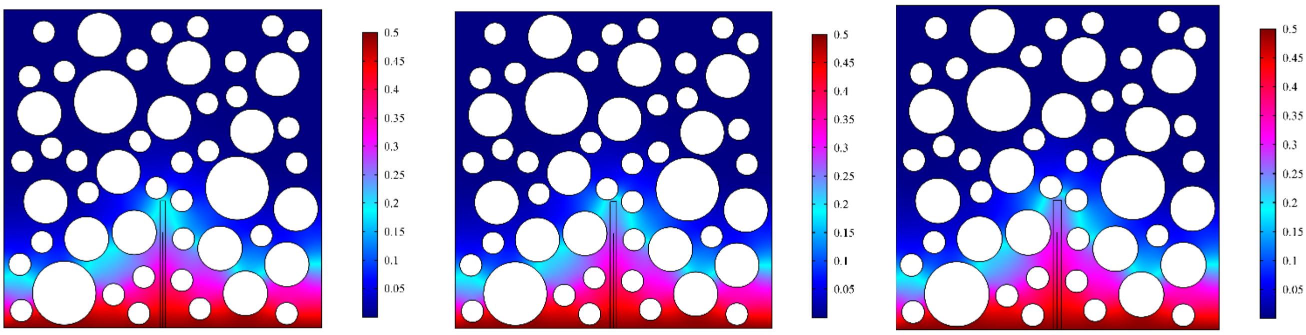


Fig. 12. Comparisons of chloride concentration profiles between three models (different lengths of the DZ)



(a) 1.5 mm (b) 2.0 mm (c) 2.5 mm

Fig. 13. Chloride concentration distributions with different widths of the damaged zone

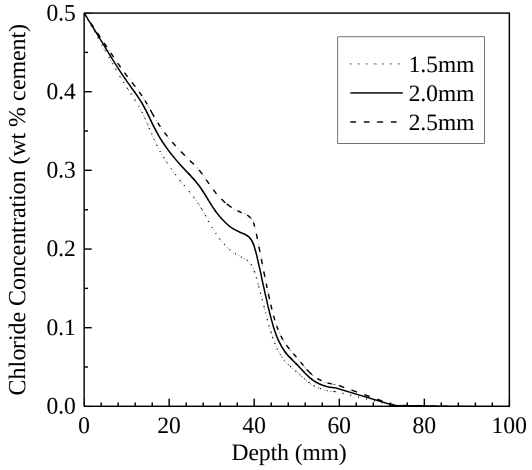
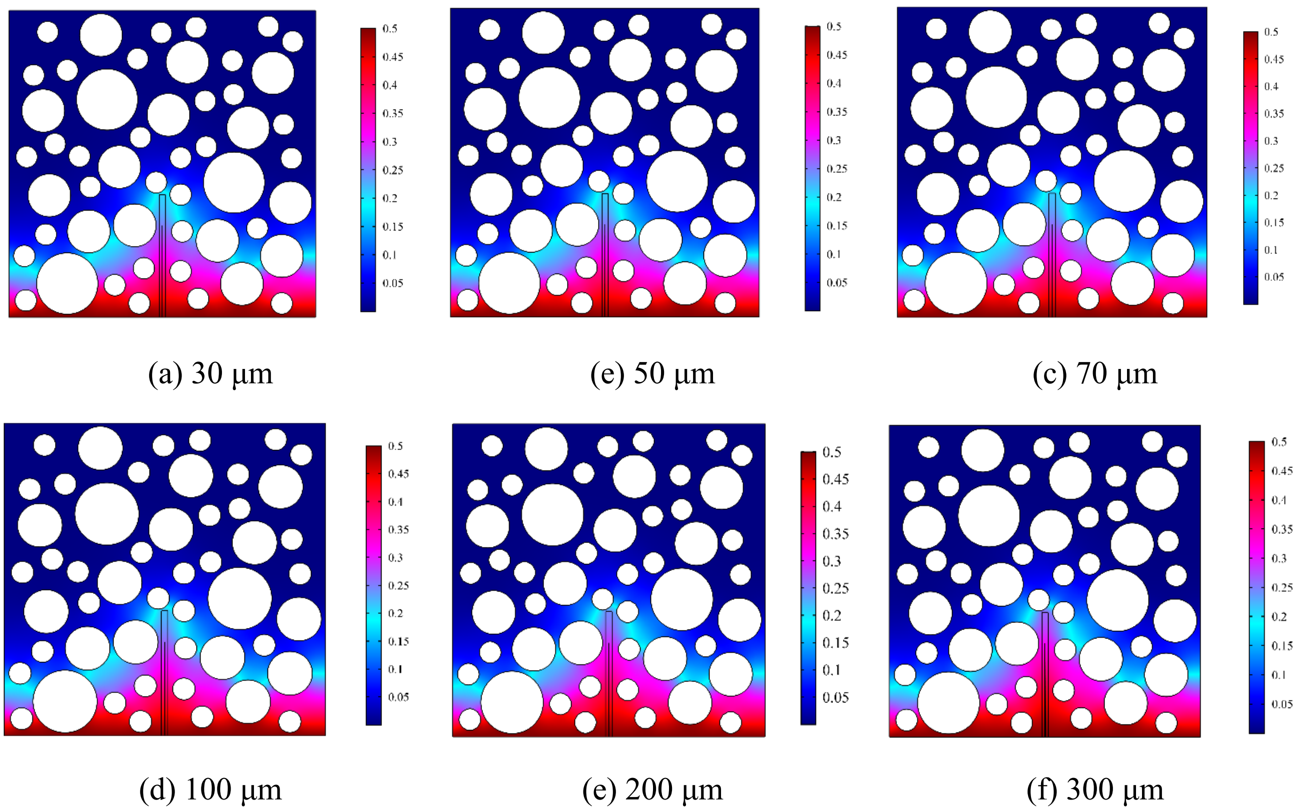


Fig. 14. Comparisons of chloride concentration profiles between three models (different widths of the DZ)



(a) 30 μm (e) 50 μm (c) 70 μm

(d) 100 μm (e) 200 μm (f) 300 μm

Fig. 15. Chloride concentration distributions with different widths of the crack

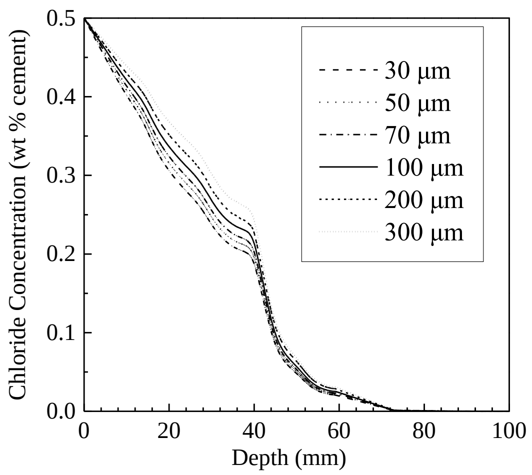
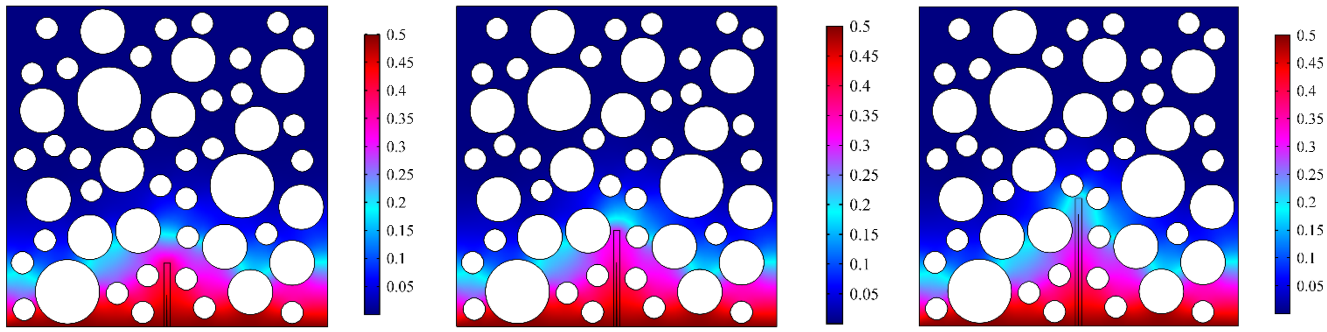


Fig. 16. Comparisons of chloride concentration profiles between different models (different widths of the crack)



(a) 10 mm (b) 20 mm (c) 30 mm

Fig. 17. Chloride concentration distributions with different crack lengths

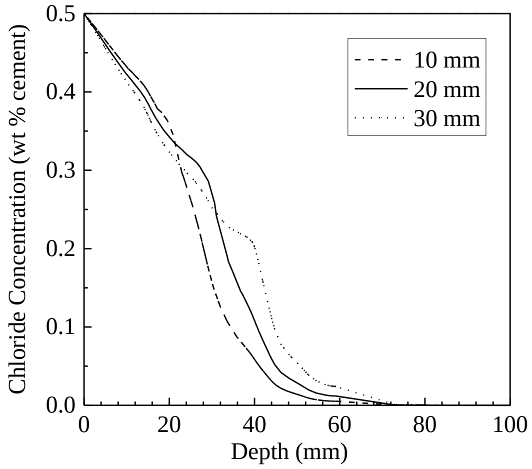
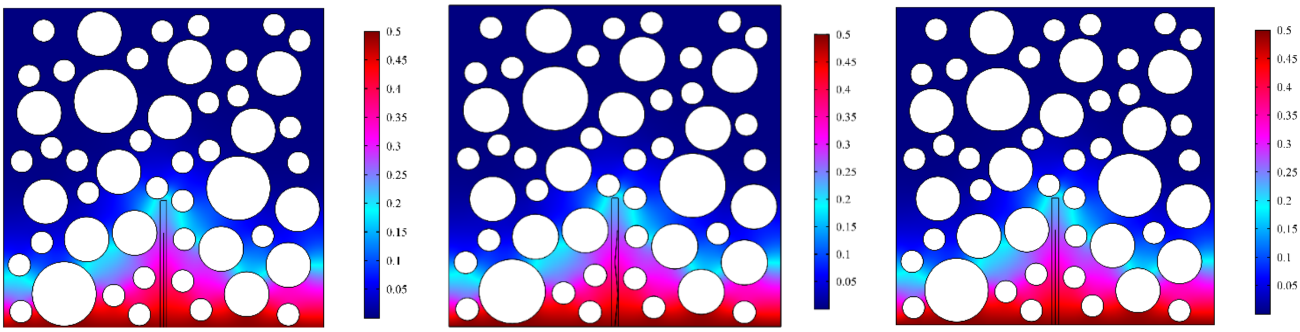


Fig. 18. Comparison of chloride concentration profiles between different models (different crack lengths)



(a) Tapered crack (b) Tortuous crack (c) Parallel-wall crack

Fig. 19. Chloride concentration distributions with different forms of the crack

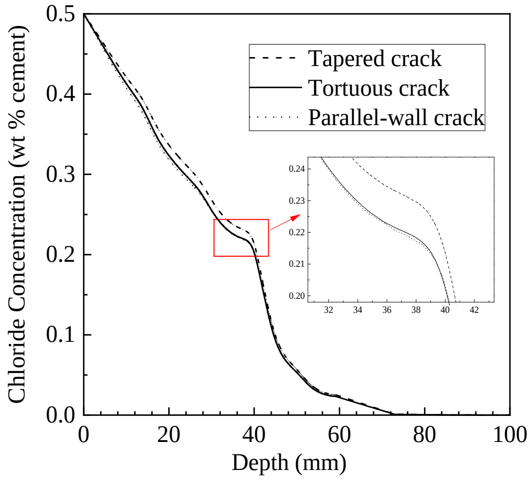


Fig. 20. Comparison of chloride concentration profiles between different models (different crack patterns)