Three-phase modelling of electrochemical chloride removal from corroded steel-reinforced concrete

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Abstract

Electrochemical chloride removal (ECR) is an efficient and curative way for treating reinforced concrete structures about to suffer or already suffering from chloride attack. In order to provide a deep understanding of the mechanisms of ECR, this paper presents a mesoscale numerical model, which considers the multi-species coupling in pore solution, electrochemical reactions taking place at electrodes, multispecies binding between solid and liquid phases, as well as the effect of applied current density and treatment time on the efficiency of chloride removal. The concrete presented in this model is treated as a heterogeneous composite material with three constituent parts, including not only mortar but also volume-controllable aggregates and interfacial transition zones; each as one phase. Through a further study on the different configurations of multiple reinforcing bars as cathodes, a quantitative discussion regarding the economic issue of different cathode configurations is highlighted. In addition, the present three-phase model reveals some important features of aggregate effects which could not be discovered from previous one-phase models.

1. Introduction

It is well known that the penetration of ions, especially chloride ions, is the main reason causing the corrosion of reinforcing steel in concrete structures. Considering both the cost and efficiency of the rehabilitation methods, electrochemical chloride removal (ECR) or electrochemical chloride extraction (ECE) is a conventional and curative way for treating reinforced concrete structures about to suffer or already suffering from chloride attack. The repair method of ECR was first reported in the 1970s [1]. The idea involves mounting an external anode surrounded by a suitable liquid electrolyte on the surface of the concrete and applying a high direct current density between the anode and the embedded reinforcing bar acting as a cathode. During a conveniently short time (usually a few weeks), most of the chlorides in the concrete are driven away from the reinforcement cathode into the external electrolyte near the anode due to the action of the applied current. As a result, the chloride-contaminated concrete can be eventually rehabilitated and its service life thus extended.

Since the invention of ECR in the 1970s, a large number of laboratory tests have been carried out to investigate the effectiveness and efficiency of the method as well as the possible side effect of the electrochemical treatment on the mechanical properties of concrete and the bond strength between reinforcement and concrete [2–25]. Apart from the experimental studies, significant progress has also been made in developing numerical models...
to simulate the process of the treatment. Concrete is a heterogeneous material with complicated microstructure organisation. Experiments can provide important and valuable data but individual effects of various factors are difficult to determine because of the interactions between the different factors [26,27]. In contrast, numerical models have the great advantage in providing detailed information and investigating parametric effects. With the advance of computer science and the progress of computational mathematics, numerical modelling becomes more and more popular, particularly for problems of complicated geometries and those involving many physical parameters. The existing numerical models of ECR often focus on obtaining the chloride distribution profiles versus time and/or space under the influence of various factors (i.e. treatment time, current density, binding effect, additives, temperature etc.) by assuming the concrete as a one- [28–38] or two-dimensional single phase material [39,40]. In most of these studies, a single cathode was used, indicating that the reinforcing bars were isolated from each other in the structure, which may not be true in reality [18]. It is obvious that if the reinforcing bars are connected together, the situation would be quite different for the ECR treatment as short circuits are produced between steel electrodes, which will obviously have an impact on the chloride removal. This kind of impact has not been properly addressed in literature. Moreover, most of the existing models use the single phase model, i.e. assuming the concrete as a homogeneous porous material. However, recent studies showed that aggregates and the interfacial transition zone (ITZ), which is the area around the aggregate where there is a porosity gradient as the cement paste close to the aggregate is less porous than the rest of the cement paste, can have significant effects on the transport of ions [41], indicating that the concrete should be treated as a heterogeneous material of multiple phases. More recently, Liu and Shi [40] presented a numerical model of ECR, which demonstrated the importance of inclusion of aggregates in the simulation of ECR and reported the results of chloride removal when the cathode is selected at different positions. However, their work did not discuss or show how the current distribution affects the chloride removal.

In this paper, a two-dimensional mesoscale model is presented, which considers the multi-species coupling in pore solution, electrochemical reactions taking place at electrodes, multi-species binding between solid and liquid phases, as well as the effect of applied current density and treatment time on the efficiency of chloride removal. The concrete presented in this model is treated as a heterogeneous composite material with three constituent parts, namely mortar matrix, aggregates and ITZs, each as one phase. Through a further study on the different configurations of multiple reinforcing bars as cathodes, a quantitative discussion regarding the economic issue of different cathode configurations is highlighted. In addition, the present three-phase model reveals some important features of aggregate effects which could not be discovered from previous single phase models.

2. Theoretical background

The ECR treatment in the present study is applied to a two-dimensional piece of concrete, which is treated as a heterogeneous composite material of three constituent parts, namely mortar matrix, aggregates and ITZs, each as one phase. Since the aggregates are much denser and have much higher resistance to ionic penetration than the other two parts, they are assumed to be impermeable. Correspondingly, the other two parts, mortar and ITZs are assumed to be two independent porous materials, in which ionic transport is taking place.

Assume that the porous material in ITZs and mortar phases is close to the aggregate is less porous than the rest of the cement paste, saturated, the pore solution in these two phases is the ideal and dilute solution, and there are no chemical reactions involved between ionic species. In this case the transport of ionic species can be expressed in terms of the mass conservation and current conservation as follows,

\[
\frac{\partial C_k}{\partial t} = -\nabla J_k \quad k = 1, \ldots, n
\]

\[
I = F \sum_{k=1}^{n} z_k J_k
\]

where \(C_k\) is the concentration, \(z_k\) is the charge number, \(J_k\) is the flux, \(t\) is the time, \(I\) is the current density, \(F = 9.648 \times 10^{-4} \text{ C mol}^{-1}\) is the Faraday constant, subscript \(k\) represents the \(k\)-th species, and \(n\) is the total number of the species contained in the mortar.

Diffusion and migration are considered as the dominated parts of ionic transport in this study; therefore, the flux of an ionic species can be described using Nernst-Planck equation as follows,

\[
J_k = -D_k \nabla C_k - D_0 C_k \frac{F}{RT} \nabla \Phi \quad k = 1, \ldots, n
\]

where \(D_k\) is the diffusion coefficient, \(R = 8.314 \text{ J mol}^{-1} \text{ K}^{-1}\) is the ideal gas constant, \(T = 298 \text{ K}\) is the absolute temperature, and \(\Phi\) is the electrostatic potential. Substituting Eq. (3) into (1) and (2), yields,

\[
\frac{\partial C_k}{\partial t} = D_k \nabla^2 C_k + \nabla \left( z_k D_k \frac{F}{RT} \nabla \Phi \right) C_k \quad k = 1, \ldots, n
\]

\[
F \frac{\partial \Phi}{RT} \nabla \Phi = - \left( \frac{I_x}{F} + \sum_{k=1}^{n} z_k D_k \frac{F}{RT} \nabla C_k \right) \frac{C_k}{\sum_{k=1}^{n} z_k^2 D_k C_k}
\]

Since the present simulation employs a 2D numerical concrete model, the current density term in Eq. (5) need be expressed in terms of its two components in a rectangular coordinate system when solving for the electrostatic potential, i.e.,

\[
F \frac{\partial \Phi}{RT} \frac{\partial \psi}{\partial x} = - \left( \frac{I_x}{F} + \sum_{k=1}^{n} z_k D_k \frac{F}{RT} \nabla C_k \right) \frac{C_k}{\sum_{k=1}^{n} z_k^2 D_k C_k}
\]

\[
F \frac{\partial \Phi}{RT} \frac{\partial \psi}{\partial y} = - \left( \frac{I_y}{F} + \sum_{k=1}^{n} z_k D_k \frac{F}{RT} \nabla C_k \right) \frac{C_k}{\sum_{k=1}^{n} z_k^2 D_k C_k}
\]

where \(I_x\) and \(I_y\) are the components of the current density in \(x\)- and \(y\)-directions, respectively. Since the current density satisfies \(\nabla \cdot I = 0\), \(I_x\) and \(I_y\) can be calculated by solving the following Laplace equation,

\[
\nabla^2 \psi = \frac{\partial^2 \psi}{\partial x^2} + \frac{\partial^2 \psi}{\partial y^2} = 0
\]

where \(I_x = \frac{\psi}{\Omega}\) and \(I_y = \frac{\psi}{\Omega}\). The boundary conditions of \(\psi\) is that, at the cathode its normal derivative equals to the externally applied current density, that is \(\frac{\partial \psi}{\partial n} = I_0\), where \(\Omega\) represents the cathode boundary, while at the anode its function value equals to zero, which enforces the conservation of current between the inward at anode and the outward at cathode.

Note that, for concrete ionic transport takes place in the pore solution and during the course of the transport of ions, some of them may be bounded to the pore surface both physically and chemically. To take into account the ionic binding, Eqs. (1) and (4) need to be modified as follows,

\[
\frac{\partial C_k}{\partial t} + \frac{\partial S_k}{\partial t} = -\nabla J_k \quad k = 1, \ldots, n
\]

\[
\frac{\partial C_k}{\partial t} + \frac{\partial S_k}{\partial t} = D_k \nabla^2 C_k + \nabla \left( z_k D_k \frac{F}{RT} \nabla \Phi \right) C_k \quad k = 1, \ldots, n
\]
where $S_k$ is the concentration of bound ions of species $k$. Experimental data [13,33,34] suggest that the relationship between the bound and free chloride concentrations is almost independent of the removal rates and approximately satisfies the Langmuir isotherm:

$$S_k = \frac{\alpha C_k}{w(1 + \beta C_k)}$$

(11)

where $w$ is the content of the water in which diffusion occurs, expressed per unit weight of mortar, $\alpha = 0.42$ and $\beta = 0.8$ mol$^{-1}$ for the constants which were determined based on the experimental data for $w = 0.3$ [13]. Hence, it is convenient to use a parameter $\lambda_k = \frac{w}{w+1+\beta C_k}$ to express the proportionality between the concentration rates of free and bound chloride ions, so that Eq. (10) can be simplified as:

$$\frac{1 + \lambda_k}{\lambda_k} \frac{\partial C_k}{\partial t} = a \nabla(D_k \nabla C_k) + \nabla \left( \frac{z_k D_k F}{R T} C_k \nabla \phi \right)$$

(12)

Note that Eq. (12) is applied only to chloride ions. Whether it can also be applied to other ionic species remains unknown. In literature there is no experimental data about the binding of other ionic species. However, because of the charge balance it is believed that other ionic binding would also take place. Therefore, in the present study, the chloride binding is used based on the experimental data [13], while the binding of other four ionic species is simply assumed based on the charge balance. This means that the bound part of chlorides $\lambda_k C_k$ is balanced by other four ionic species, with $-\lambda_k C_k = \lambda_k C_k$ contributed by hydroxyl ions, $\lambda_k C_k$ contributed by each of the three positive ionic species.

In summary, Eqs. (8) and (12) can describe the ionic transport in a saturated pore medium. The concentration profile of each ionic species and the gradient of electrostatic potential can be obtained for a given current density distribution if initial and boundary conditions of them are properly provided. Note that when Eq. (12) is applied to multi-phase pore medium (i.e. mortar phase and ITZs in this study), one has to use individual transport properties for each phase, whereas continuous conditions are imposed for both concentrations and fluxes at the interfaces between different phases. The details of the geometric modelling of the concrete of multi-phases will be given in following section.

3. Numerical simulation

A numerical simulation is conducted to predict ECR applied to a plain concrete specimen for a period of 12 weeks. The concrete specimen is modelled as a square plate of side length $L = 50$ mm. Four reinforcing steel bars of 5 mm radius are equally spaced in the specimen as shown in Fig. 1. Initially, the concrete specimen is saturated with a solution of five ionic species, potassium, sodium, chloride, hydroxyl and calcium. Externally, a constant direct current (DC) is applied between the reinforcing steel bars and an anode placed on the left side of the specimen. The anode is inserted into a suitable compartment of electrolyte, which has a much greater volume than the concrete specimen. More notably, to investigate the effect caused by different cathode configurations, the cathode is arranged into three different cases. Case 1 is only when the right side bars are connected; Case 2 is only the left side bars are connected; Case 3 is all bars are connected. The steel bars which are connected are assumed to have the same current density, the value of which is equal to the externally applied current density. The three cases of different cathode configurations will be examined separately in the following ECR modelling.

Apart from the cathode configurations, the effects of aggregates and ITZs are also quantitatively examined in this study by using a series of two-dimensional, three-phase FEA models with various aggregate volume fractions ($V_a$). It may be noticed from Fig. 1 that, both the electrode setting and geometry of the specimen in each case are symmetric about the horizontal central line. Hence, for the simplification of investigation, only a half of the specimen, 50 mm × 25 mm, is modelled. Fig. 2 shows one of the three-phase models adopted in this simulation ($V_a = 0.5$), in which the circular areas represent the impermeable aggregates (except for the two steel bars, whose centres are respectively located at $x = L/4$ and $x = 3L/4$) with the radii ranging from 1.5 mm to 10 mm. These aggregates are randomly generated in the geometry by using MATLAB software. Note that though the shape of aggregates may not be such perfectly circular in reality, particle shape only makes a modest influence on the transport properties of concrete according to the previous studies [42,43]. Outside each aggregate, there is an aureole ITZ shell wrapping the aggregate. Note that the real thickness of ITZs in normal concrete is only 20–50 μm [44,45]. However, this kind of thin layer creates some difficulty in the element mesh of ITZs due to the computing limitation; therefore, the ITZ layer in the present model is artificially increased to 100 μm. In order not to overestimate the ITZ effect, the increase of the ITZs volume in the present model is compensated by the reduction of the diffusion coefficients of ions in the ITZs. Outside the ITZs, the remaining part of the concrete model represents the mortar matrix. Fig. 3 shows the corresponding finite element mesh used. As the aggregate phase (white area) is assumed to be impermeable as well as the ionic transport takes place only in the mortar and ITZ phases, only the latter two phases are meshed.

The basic settings (i.e. boundary and initial concentrations, the charge number and diffusion coefficients) of the five individual ionic species used in the simulation are shown in Table 1. It should be mentioned about the diffusivities that, existing data show that the ratio of diffusion coefficients of ions in ITZs and in bulk cement paste is about 4–15, depending on the porosity and water-to-cement ratio of individual specimens [46–48]. However, as aforementioned, considering the use of a large value for the thickness
of ITZs in the geometric models, the diffusion coefficient in the ITZ phase for each ionic species here is taken as three times that for the mortar phase.

When the current is applied through the two electrodes electrochemical reactions at the two electrodes will take place. In general, during the ECR treatment, the following electrochemical reactions occur at the cathode,
2H$_2$O + O$_2$ + 4e$^-$ \text{electrolysis} \rightarrow 4OH^- \tag{13}

2H$_2$O + 2e$^-$ \text{electrolysis} \rightarrow 2OH^- + H$_2$ \tag{14}

And at the anode,

4OH$^-$ \text{electrolysis} \rightarrow 2H$_2$O + O$_2$ + 4e$^-$ \tag{15}

2H$_2$O \text{electrolysis} \rightarrow O_2 + 4H^+ + 4e^- \tag{16}

Eqs. (13)–(16) imply that hydroxyl ions will be generated and destroyed at the cathode and anode, respectively. These generated or destroyed hydroxyl ions are in equivalent to provide an inward and an outward flux of hydroxyl ions. Mathematically, these fluxes are related to the current density externally applied, i.e.

\[ J_{\text{OH}} = \frac{I_0}{F} \tag{17} \]

Unlike the hydroxyl ions, the other four ionic species at cathode have zero flux and thus their boundary conditions are,

\[ J_{k, \text{in}} = 0 \quad k \neq \text{OH} \tag{18} \]

The boundary conditions at the anode are provided in Table 1.

4. Simulation results and sensitive analysis

4.1. Cathode configurations

One of the purposes of this study is to examine how the cathode configuration affects the performance of ECR. For this purpose, a
constant current density of $5 \text{ A/m}^2$ is applied in each of the three mentioned cases. By solving the mass conservation and Laplace equations, the results of current density and concentrations of the five species are obtained. Fig. 4 respectively depicts the current flow patterns in the three cases, in which the colour legend shows the magnitude of the current density and the arrow shows the orientation of the current flow. It is observed from the figure that, overall the current flows from the anode to the cathode and at the edge of an aggregate the flow is along its tangent direction. Also, it can be seen from the colour legend that, the current density in the region between anode and central cathode is much higher than that in the region behind the steel bar and far away from the anode. Note that some of the arrows around the steel cathode do not exactly point toward the centre of the circular bar. This is due to the effect of the current density along the tangent direction at the boundary, as the plot provides the magnitude and direction of the current density vector.

As is to be expected, the current flow in Case 2 (single left cathode) (see Fig. 4b) occurs mainly in the left region of the specimen between the anode and the steel bar that acts as a cathode. In contrast, the current flow in the other two cases (see Figs. 4a and 4c) is widely distributed in the whole area of the specimen. For Cases 1 and 3, though the two patterns are similar they do have distinct features. First and more obviously, the orientations of current flows around the two steel bars are both inward in the double cathode configuration although the inward flow around the left bar seems very close to the tangent direction, whereas in the single right cathode configuration, the current orientations are tangential to the left bar, which behaves as an aggregate. Moreover, from the observation of colour legends, Case 3 has the larger magnitude of

![Fig. 5b. Distribution profiles of ionic concentration for Case 2.](image-url)
Fig. 5c. Distribution profiles of ionic concentration for Case 3.

Fig. 6. Comparison of different cathode configurations on chlorides removed from specimen by ECR.

Fig. 7. Comparison of different cathode configurations on daily rate of chloride removal from specimen by ECR.
Fig. 8. (a) and (b). Distribution profiles of ionic concentration for 1 mA/m².
current density and interestingly its value approximately equals the sum of the other two cases (including the maximum). This reveals that the distribution of current density in the double cathode configuration superimposes those in the two single cathode configurations. The last but not least, with a more careful examination on the colour legends from the anode to the right cathode, one may notice that the current density value in Case 1 is distributed more evenly than that in Case 3. As is shown in Fig. 4c, the density
magnitude in the region from the anode to the left cathode is much larger than that in the region between the two cathodes. The most likely reason for this phenomenon is that the presence of the left cathode delays the current flow in the region between the two bars, which indicates that the double cathode configuration may cause a certain degree of energy waste during the ECR treatment.

Fig. 9. (a) and (b). Distribution profiles of ionic concentration for 3 A/m².
especially in the areas between the steel bars when they are acting as the cathode.

Additionally, from the zoom view shown in Fig. 4d, one may find that the current flow around each aggregate displays as pairs of double arrows, which reflects the influence of ITZs; this kind of feature cannot be found in any one- or two-phase models.

The 3-D plots shown in Figs. 5a–5c provide a good view on the concentration distributions of potassium, sodium, chloride and...
hydroxyl ions under a 12-week ECR treatment, obtained in the three cases discussed above, in which the two plane coordinates represent the position of the variable in the two-dimensional concrete model and the vertical coordinate is the value of concentration. Due to the much lower concentration, the profiles of calcium ions are not shown there. It is clear from Figs. 5a–5c that, the profiles of different configurations are qualitatively similar. The concentration always reaches the lowest value at the left boundary.
due to the effect of boundary condition there. Also, the concentration around the cathode forms as convex for the positively charged ions (i.e. potassium and sodium) and as concave for the chloride ions. Notably, for the negatively charged hydroxyl ions, the concentration around the cathode forms not as concave like the chlorides but as convex like the two cations. This is due to the
electrochemical reactions taking place at the steel cathode (Eq. (13)), which provides an inward flux for the hydroxyl ions. It is noted that the flux generated at the cathode is quicker than the flux flow away from the cathode. Consequently, the concentration of hydroxyl ions increases with the treatment time, as is demonstrated in Fig. 5b.

Figs. 4 and 5 only offer a qualitative comparison on the effect of cathode configuration. For a better understanding of the performance and efficiency of the ECR treatment employed in the three different cases, Fig. 6 shows the relationship between the total amount of chlorides removed from the specimen and the treatment time. The total chlorides removed are calculated from \( J_{Cl}^{20} = \int_0^\tau J_{Cl} \text{d}t \), where \( J_{Cl} \) is the flux of chlorides at the boundary \( x = 0 \) and the time used for the comparison \( \tau \) is from 1 day to 84 days. It is seen from Fig. 6 that, among the three different cathode configurations the double cathode configuration has the highest removed chlorides, whereas the single left cathode configuration has the lowest removed chlorides. Note that the total currents applied in the two single cathode configurations are identical and the total current applied in the double cathode configuration is twice that in the single cathode cases. Therefore, although the double cathode configuration has the best performance, it is not the best in terms of the efficiency since the sum of the removed chlorides in the two single cathode cases is larger than the removed chlorides in the double cathode case. In order to conclude this finding, a simulation using the double cathode configuration with a low current density is in between the results of the two single cathode cases. This suggests that the longer the distance between the anode and cathode, the better the performance of ECR that can be obtained. This conclusion is further demonstrated by the results shown in Fig. 7, which illustrates the daily removal of chlorides in each discussed case. Though all three cases experience an efficiency drop on the chloride removal during the treatment period, the single right cathode configuration has the most moderate downward trend and thus the best efficiency. The removal rate in the single left cathode configuration or double cathode configuration drops quickly when compared to the single right cathode configuration and becomes constant after about 20 days, whereas in the single right cathode configuration the removal rate becomes constant after almost 40 days.

4.2. Current density

Based on the foregoing discussion, it is suggested that Case 1, the single right cathode configuration, is the most prudent choice for ECR. Therefore, this type of cathode configuration is adopted for the further study to examine the effect of current density. Figs. 8–10 respectively show the concentration distributions of the four species under the influence of a small (1 mA/m²) and two large (3 A/m² and 5 A/m²) current densities. Each frame of individual variable represents one instantaneous moment from the 4th week to the 12th week. Fig. 8 shows the concentration distribution profiles corresponding to a current density of 1 mA/m² applied to the steel cathode. It is revealed that, under such a low current density, the transport of ionic species is dominated by the diffusion process, in which all of ions shown move towards the anode where their concentrations are relatively low. The steel cathode does not have much influence on the transport process since the movements of ions almost entirely take place along the x-axis but rarely occur in the y-axis direction (The few extraordinary cases which happened along the y-coordinate are simply because the tortuosity effect caused by the aggregates phase). Also it can be found from the figure that, the ionic species of higher diffusion coefficients (i.e. hydroxyl) move more rapidly than those of lower diffusion coefficients. As the applied current density increases, the migration plays an increasingly significant role in the transport process. It can be seen from Fig. 9 that, when the current density applied to the steel cathode reaches 3 A/m², the transport behaviour is much different from that shown in Fig. 8. The maximum concentration values of the figures shows that the chloride ions are steadily removed from the region close to the steel with increased treatment time, whereas potassium and sodium ions do the opposite. In terms of the hydroxyl ions, they also migrate from cathode to anode like chloride ions do, but on the other hand, they increase along the cathode boundary because of the electrochemical reactions taking place at the cathode as previously mentioned. Emphatically, though the performances between hydroxyl and the two positively charged ionic species are similar, the essences are rather different. It also can be seen Fig. 8 that, since the current flow exists mainly between two electrodes as explained in Fig. 4, the ionic transport in the region behind the central steel is still controlled by diffusion, which makes the removal of ions in that region more difficult. The migration process remains dominant between the two electrodes when the applied current density increases further. Fig. 10 describes the ionic concentration distribution profiles with the current density of 5 A/m² applied at the steel cathode. It can be found from the figure that, with the larger current density, more chloride ions move away from the steel cathode while more potassium and sodium ions move towards the cathode. Hydroxyl ions increase more quickly at the cathode although part of them move away from the cathode to the anode. However, this upward trend does not experience markedly for the region behind the steel where the diffusion process dominates. This means that the increase of current density causes very little influence on ECR at the places where there are no electrodes clamped. The 2-D plot of the total chlorides removed from the specimen shown in Fig. 11 gives a detailed comparison of the effect of applied current density. It is shown that the larger the current density applied, the more chlorides can be removed.

4.3. Aggregate and ITZ phases

To explore the influence of aggregates and ITZs on the performance of ECR, a set of simplified simulations are conducted, in
which all aggregates and ITZs are removed from the above three-phase model. The results of concentration distributions when a current density of 5 A/m² is applied are shown in Fig. 12. A careful comparison between Figs. 10 and 12 shows that the three-phase model (aggregate volume fraction of 0.5) can transport more ions than the one-phase model does, both in amount and speed. This is mainly because that, for a given current density applied at a steel bar the inclusion of aggregates in concrete leads to larger current

Fig. 12. (a) and (b). Distribution profiles of ionic concentration for 1-phase model.
density in the mortar phase and thus accelerates the transport of ions and increases the removal of chlorides. From the comparison of concentration profiles, it seems that the concentration profiles in the three-phase model with an external current density of 3 A/m² match well with those in the one-phase model with an external current density of 5 A/m². However, it should be mentioned that,
the presence of aggregates will also increase the tortuosity effect and thus have a negative impact on the transport of ions [40,41]. Furthermore, the total chlorides removed are also dependent on the porosity. The higher the porosity, the more the chlorides can be removed. Of interest is which of these two opposite effects is dominant in terms of the chloride removal. Fig. 13 shows a comparison of the total chlorides removed by ECR obtained from one- and three-phase models for two different current densities, respectively. It is interesting to find from the figure that the difference between total chlorides removed from the specimen predicted by the two models is dependent on both the current density and treatment time. In the short period the one-phase model predicts higher chloride removal, whereas in the long term the three-phase model predicts higher chloride removal. However, the difference between them seems not very significant. This indicates that the effect of the increase of current density in mortar due to the presence of aggregates on the ECR treatment can more or less compensate the effect of the increase in tortuosity and decrease in porosity caused by the presence of aggregates.

5. Conclusions

This paper has proposed a three-phase numerical model to investigate the performance and efficiency of ECR treatment. Based on a series of parametric analyses on the influence of multiple cathodes, current density, treatment time and inclusion of aggregates, the following conclusions can be drawn.

(1) The choice of cathode in ECR treatment is very important. Not only can it affect the performance but also the efficiency of the treatment. For the three cases discussed, the single right cathode configuration provides the most efficient way in removing chlorides.

(2) The amounts of removed chlorides increase with the externally applied current density and treatment time. However, the daily removal rate of chlorides will decrease with the treatment time, indicating that the efficiency of ECR drops also with the treatment time.

(3) There are twofold effects of aggregates on the model prediction of the ECR treatment. One is the increase in current density due to the reduction in area where current can flow; the other is the changes of tortuosity and porosity. However, in terms of the total chlorides removed by ECR, these two opposite effects provided by the presence of aggregates can approximately cancel each other.

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