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Progress and research challenges in concrete durability: ionic transport, electrochemical rehabilitation and service life prediction

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Abstract

Concrete durability degradation problems have received considerable attention in both research field and concrete industry during recent decades. To better understand the underlying mechanisms, various numerical models have been put forward aiming at widely concerned scientific issues involved in the entire life cycle of concrete structures: ionic transport in porous medium, degradations induced by multiple factors, as well as the prediction and rehabilitation method to prolong the service life. This letter aims to summarise the major contributions to these interrelated scientific issues particularly from the modelling perspective. The digital characterization of concrete heterogeneity and its influence on ionic transport behaviour will be firstly reviewed. Subsequently, concrete deterioration mechanisms induced by various factors and their internal coupling relationships are discussed in details. Meanwhile, promising electrochemical repair techniques with multi-fold advantages including chloride removal, corrosion inhibition, ASR mitigation and crack repair are systematically summarized. Finally, existing research gaps and future opportunities in these areas have also been visited, which is hoped to break the ice in this challenging field and promote the sustainable development of the concrete industry.

Keywords: Multi-species transport; Multi-phase; Chloride; Concrete durability; Electrochemical rehabilitation

1 Introduction

The durability degradation problems of concrete structures have become one of the biggest challenges for the sustainable development of the concrete industry. The synergistic action of aggressive salts and harsh environments is considered to be mainly responsible for the degradation of concrete durability, and the complex interaction between them makes the deterioration behaviour even more difficult to predict [1]. Consequently, concrete durability deterioration mechanisms have attracted increasingly more attention from both academic and engineering societies. Generally, the entire process during the service life of concrete structures can be covered by three interrelated stages: deleterious ions penetration, durability degradation and the subsequent repair application. To better understand this life cycle process which involves a large time span and a wide range of disciplines, there remain some representative key scientific challenges that need to be further revealed and addressed from the perspective of mechanisms to practice.

Firstly, what is the intrinsic mechanism of multi-species transport in multi-phase concrete? Ionic transport in concrete constitutes the initial stage for many durability problems such as chloride-induced corrosion, and it, therefore, forms the basis for accurate prediction of concrete service life. It has been commonly acknowledged that concrete is a heterogeneous material, especially at the mesoscale and microscale, where the multi phases in concrete will affect the ionic transport and degradation process at varying degrees [2]. In addition to the widely concerned chloride ion, it should also be highlighted that other ionic species including sodium, potassium and hydroxide and calcium ions also coexist in pore solution, and some of them even fundamentally influence the chemical and mechanical properties of concrete [3, 4]. Therefore, when investigating the ionic transport in concrete, it is important to take the inherent heterogeneous nature of concrete and interactions among various ionic species into account to ensure more accurate and reliable prediction results.

Secondly, how to better understand the mechanisms of various concrete durability problems and their mutual interactions to predict the service life? Based on the understanding of ionic transport in concrete from the perspective of multi-ion and multi-phase, new findings on the ingress of deleterious ions would shed light on the

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understanding of the durability degradation process as well as the service life prediction. It should be noted that although chloride-induced corrosion is the dominant degradation phenomenon, other durability problems such as carbonation [5], sulphate attack [6], calcium leaching [7], alkali silica reaction [8], freeze-thaw cracking [9], and other durability degradations facilitated by load-induced cracking [10] would appear in junction with the chloride ingress. Therefore, it would be still a challenge to couple the interactions between multiple degradation mechanisms and concrete performances by using the language of mathematics and modelling [11], which could provide a unique perspective to discuss what has been faced in concrete engineering practice. Based on the coupling of multi deterioration factors, the service life of concrete structures can also be more accurately and reliably predicted.

Thirdly, when and how to repair existing reinforced concrete structures which are about to suffer or have already suffered from durability diseases? Aiming at different durability problems, numerous electrochemical rehabilitation methods [12-14] and electrochemical protection methods [15, 16] have been put forward in recent decades, and nearly all of them involve the transport behaviour of multiple ionic species. Due to the involvement of the external electric field the interaction and coupling among various ions will also get enhanced, and electrochemical and chemical reactions happening on the electrode surface and pore solution during the treatment will make the ionic transport much more complex and even difficult to predict. In addition, different durability deterioration will lead to various damage characteristics of concrete, so the repair objectives can also be diversified. However, traditional electrochemical rehabilitation methods are typically designed to be effective for one kind of durability deterioration factor: electrochemical realkalisation for concrete realkalisation and steel repassivation, electrochemical chloride removal for chloride removal and electrochemical deposition for crack healing. For reinforced concrete structures serving in engineering practice, they are commonly threatened by various degradation factors. Therefore, it is of great significance to find an effective method with multiple advantages to cover these repair objectives as much as possible, which is beneficial to prolong the service life of concrete structures in a more efficient way. Otherwise, inappropriate repair strategies will cause secondary damage to reinforced concrete structures.

In view of the abovementioned key scientific concerns, extensive mechanism studies and practical applications have been conducted in the past decades, and remarkable progress has been made and documented. In this paper, major contributions in the corresponding fields: multi-species transport, concrete service life prediction, and electrochemical rehabilitation will be reviewed and highlighted in the following sections. Concluding remarks, research challenges and opportunities will also be discussed, hoping to better guide future research and facilitate academic communications in this field.

2 Multi-species transport in multi-phase concrete

2.1 Multi-phase components in concrete matrix

Concrete can be regarded as a multi-phase material containing coarse aggregates, fine aggregates, hydrated cement phases, interface transition zone (ITZ), microcracks, water, air bubbles and other structures. Each phase has distinct transport properties, and their distribution in cement bulk will also contribute to the transport path tortuosity which inevitably influences the ionic transport behaviour [17]. The most accurate method to characterize the heterogeneous nature is the X-ray CT image [18], which can distinguish different phases in a grayscale image through the unique dielectric constants of each component [19]. However, X-ray CT is often limited by image resolution, which makes it difficult to characterize the smallest phases in cement paste. Besides, the scanning procedure is time-consuming and the image processing also requires a high computational cost [20]. In addition to being directly generated from X-ray CT images, the multiphase composition of concrete can also be generated by a random algorithm. Low polyhedron (polygon in 2D) generated by a random algorithm has also been widely adopted to depict coarse aggregates with certain angularity [21]. But the irregular aggregate shape will also induce overlapping problems during the packing stage [22], so Xu and Chen have proposed an efficient contact detection algorithm for particle generation in three-dimension [23]. The most simplified and convenient method to represent aggregates is using the Euclidean geometries of sphere or ellipsoid (circle or ellipse in 2D) [24].

As for the influence of concrete heterogeneity on ionic transport behaviour, Abyaneh et al. [25] found that the aggregate shape and volume fraction both had an obvious effect on the combined transport of ionic diffusion and capillary absorption. Then, Liu et al. [26] reported the aggregate shape would influence not only the tortuosity of ionic transport path but also the distribution of electrostatic potential under the action of the external electrical field. Moreover, to quantify the pros and cons of these methods for approximating real aggregates morphology, Chen et al. [27] investigated the aggregate shape effect by digitally constructing aggregate in various shapes including ellipsoids and polyhedrons, as shown in Fig. 1, and they found that even under pure diffusion condition, the concrete diffusivity is still influenced by the shape of coarse aggregates. In addition, the characterization of ITZ in concrete has also received extensive attention. Based on the two-dimensional image information, Li et al. [28] successfully quantified ITZ thickness and predicted the concrete diffusivity in three-dimensional space.

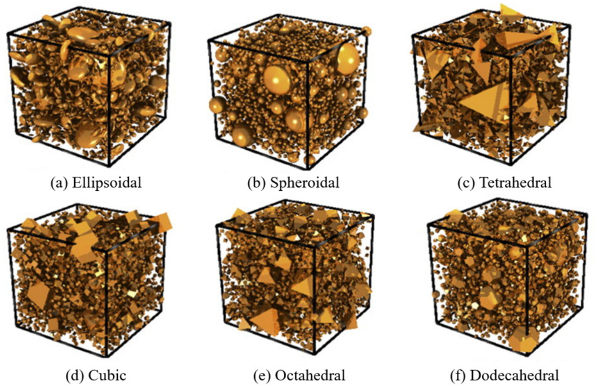

Figure 1. Schematic diagram of the multi-phase representation of concrete heterogeneity and random generation and packaging of coarse aggregates. Adapted from [27].

2.2 Multi-species transport in concrete pore solution

Although it has been acknowledged that various ionic species coexist in concrete pore solution, as one of the most deleterious ions, the ingress of chloride into concrete has firstly received considerable attention. With the rapid development of computer science and numerical modelling, and also its strength in saving test time and cost, the establishment of numerical prediction models has attracted more scientific attention. Fick's law has been widely adopted to depict the penetration of single chloride species [25, 29, 30]. Subsequently, the thermodynamic modelling approach has been adopted to depict the chemical reaction between ionic species and the hydrated cement system [31, 32]. In the light of Snyder and his colleagues [33, 34], the influence of the electrochemical coupling effect among various ionic species in pore solution was addressed. Actually, in concrete pore solution with the coexistence of multi-ions, each ionic species has distinctive features in ion radius and chemical activity, which leads to different diffusion coefficients and electrification of each ion. As a result, a local charge imbalance will be generated in the pore solution, and the induced electrostatic potential will in turn exert a nonnegligible effect on ionic transport. On top of that, Samson and Marchand [35, 36] adopted the ion exchange theory and chemical equilibriums to depict the physical and chemical reactions between various ions and cement hydration products. Johannesson et al. [37] considered the reaction kinetics and further developed a reactive multi-ionic model for concrete.

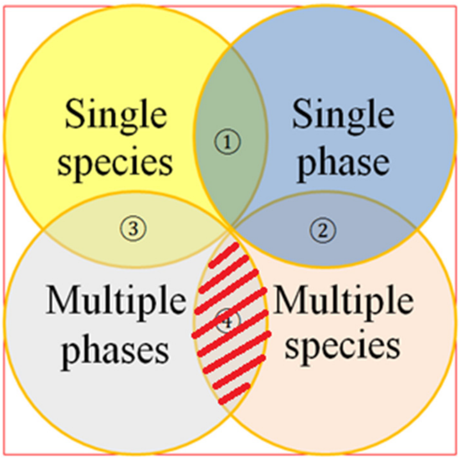

Figure 2. Categories of ionic transport models in concrete: (1) single phase, single species model, (2) single phase, multi-species model, (3) multi-phase, single species model, and (4) multi-phase, multispecies transport model ("double multi" model). Adapted from [38].

It cannot be denied that the abovementioned studies have greatly promoted the development of this field. However, as shown in Fig. 2, most studies considered multiphase but only took chloride ions into account or simply assumed electric neutrality condition. Although other studies considered multi-ion coupling, the influence of multiphase was not explicitly expressed. As a result, the "Double Multi" model has been proposed by Liu's group to potentially bridge the aforementioned research gap, and extensive studies have been carried out to further investigate the underlying mechanisms of ionic transport in concrete [39]. It has been found that ions with the same charge number possessed similar transport behaviours even though their diffusion coefficients and initial concentrations are distinctively different [38, 40]. The "Double Multi" model was also applied to predict the ionic transport in cracked concrete [41], and results showed that considering the multi-ions coupling effect can increase the prediction accuracy, and the existence of cracks will contribute to a more significant multi-ions coupling effect. As for the RC structures serving in the high incidence area of corrosion, i.e., the tidal and splash zones, it can be seen from Fig. 3 that after only 10 dry-wet cycles, the chloride concentration predicted by the model considering the multi-ions coupling effect was 1.26 times of the model only considering chloride ion [42], and the "Double Multi" model also yielded more accurate results compared to the model only considering chloride ions. In addition to the abovementioned application in concrete scale, Feng et al. [43] have also employed the "Double Multi" model to characterize the Electrical Double Layer (EDL) effect caused by the electric charges around cement particles under the cement scale.

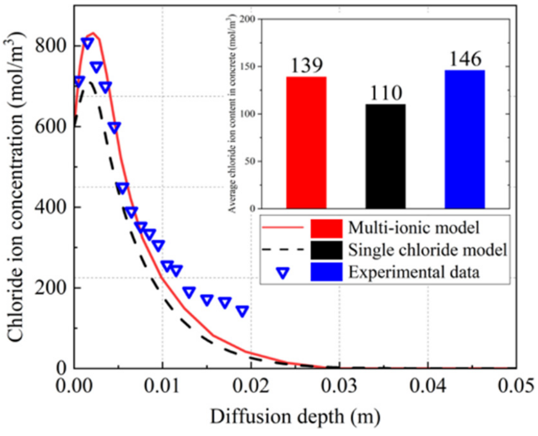

Figure 3. Chloride concentration comparison among multi-ionic model, single chloride species model and experimental data after 10 drying-wetting cycles. Adapted from [42].

3 Coupled deterioration mechanisms and durability prediction

Basically, the concrete durability deterioration factors can be classified into two categories: chemical attack such as the most common chloride-induced corrosion, sulfate-induced expansion, calcium leaching, and alkali silica reaction; physical damage such as freeze-thaw damage induced by temperature variance and cracking induced by loading. However, as mentioned previously, concrete durability problems often appear in a combined manner, the deterioration mechanisms for concrete under the combined attack of multiple damage factors are consequently more complicated. In this regard, finding a mathematical and physical expression of the concrete durability degradation problems is challenging but able to provide an efficient way to characterize the degradation process and serves as the basis for the subsequent parametric analysis, and the predicted service life would also become a strong and reliable reference for engineering practice. It should be noted that although service life is not only influenced by durability issues but also other conditions, numerical prediction models on concrete durability are hoped to serve as the basis for the service life prediction. In the following texts, some typical examples of the coupled deterioration processes will be given to illustrate this scientific issue in more details.

3.1 Coupled deterioration of carbonation and chloride ingress

The carbonation has a dual effect on chloride ingress. On the one hand, carbonation could accelerate chloride penetration by releasing previously bound chloride in Friedel's salt [44], and on the other hand, carbonation can decelerate chloride ingress by forming $CaCO_3$ and decreasing concrete porosity for ordinary Portland cement systems [45]. Therefore, how to quantitively characterize this double-fold effect is still one of the most challenging problems for concrete durability prediction, and numerous indexes to describe the carbonation process have been proposed including intensity of $CaCO_3$ [46], carbonation degree [47], carbonation front [48] and carbonation rate [49].

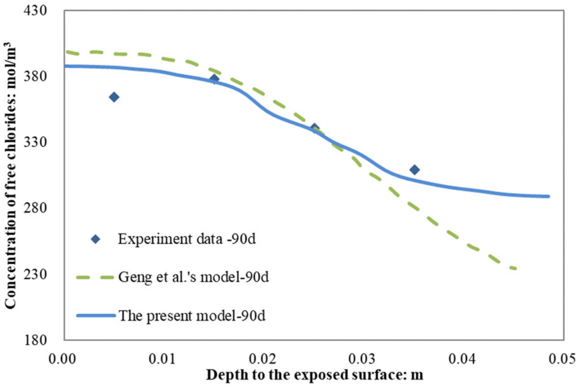

Figure 4. The comparison among experimental results, Geng et al.'s [50] fitting results and the numerical results. Adapted from [51].

In a recent study by Shen et al. [51], the carbonation rate is integrated into the chloride binding equation, and the release of bound chloride ions due to carbonation has been directly and quantitatively characterized by the equation below

$$\frac{\partial C_b}{\partial t} = -k_b\left(C_b - \left(1-k_r c\right)\frac{\alpha C_f}{1+\beta C_f}\right) \tag{1}$$

where C_b denotes the bound chloride concentration; C_f denotes the free chloride concentration; k_b denotes the chloride binding rate; k_r is the influencing coefficient of de-bounding degree; c is the carbonation rate, and α and β are chloride binding constants. Then, the chloride transport equation integrating the carbonation rate can be derived as

$$\frac{\partial C_f}{\partial t} + \frac{\partial C_b}{\partial t} = \left(1-\xi c\right) D \frac{\partial^2 C_f}{\partial x^2} \tag{2}$$

where ξ stands for the chloride diffusion effect on concrete porosity, and D stands for the initial chloride diffusion coefficient before carbonation. The prediction results against measurement results are shown in Fig. 4. It can be seen that the prediction results are even more consistent with the fitting model based on the experimental data itself. Moreover, it was also interesting to find that the negative effect of carbonation on releasing the bounded chloride is dominated, and the boundaries between the none-carbonated zone, carbonating zone and fully-carbonated zone can be clearly distinguished by the numerical calculation. The model is also able to better explain some interesting phenomena during the binary attack (e.g., the increasing content of bound chlorides in the fully-carbonated zone) from a more fundamental perspective. Based on these mathematical and physical based coupling equations, Liu's group further develop a model for combining the ingress of chloride and carbonation in unsaturated concrete as illustrated in Fig. 5, which is more suitable for the RC structures exposed to the marine environment and can make a better understanding on the effects caused by temperature, humidity, and carbon dioxide concentration [47].

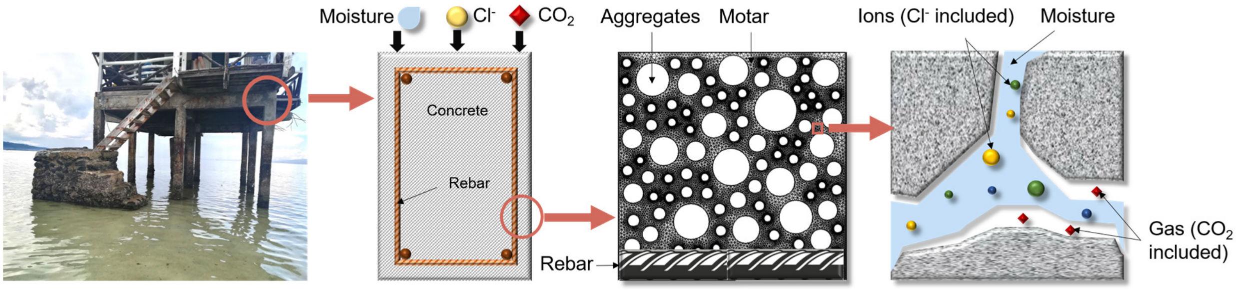

Figure 5. Schematic diagram of dual attack of chloride ingress and carbonation in unsaturated concrete. Adapted from [47].

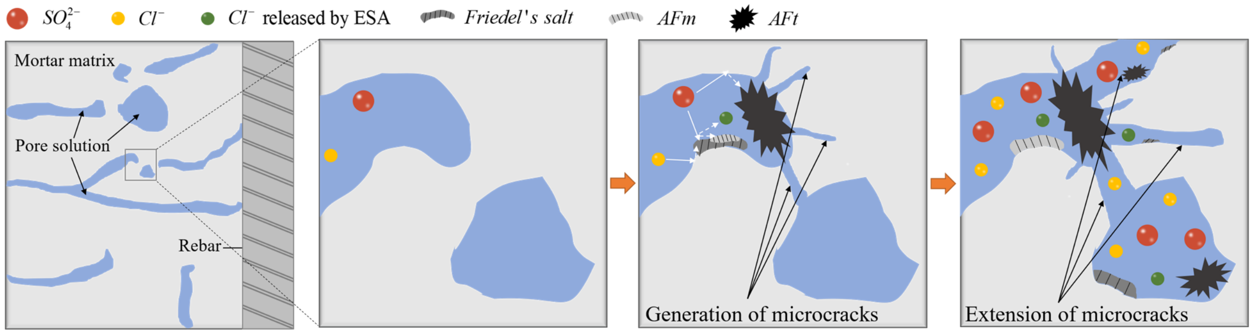

Figure 6. Schematic diagram of the competitive antagonism during the combined chloride-sulfate attack. Adapted from [58].

3.2 Coupled deterioration of sulfate attack and chloride ingress

Similarly, as shown in Fig. 6, the two-fold effect also exists in the combined chloride-sulfate attack, and it has also been realized that the chloride and sulfate ions would have a competitive antagonism in their reactions with the hydrated cement system [52]. The penetrated sulfate ions would on the one hand react with calcium aluminate phases to produce expansive products and retard the subsequent ingress of chloride [53, 54], and on the other hand, would release previously bound chloride and induce expansive cracks to facilitate the chloride ingress [55]. In recent years, a few numerical models have been developed and can be divided into two categories. The first one this based on the thermodynamic modelling approach where chemical equilibriums in cement hydrated components and precipitation products can be taken into account [56]. The second utilizes the reaction kinetics to characterize product formation during the combined chloride-sulfate attack [57, 58]. However, most of these studies take the assumption that concrete is a homogeneous material and the influence of multi-ions coupling on this two-fold effect has not yet been quantitively studied. Future research on this prospect may help to better understand this complex but interesting degradation process, which can contribute to a more accurate service life prediction for concrete in saline environments.

3.3 Coupled deterioration of calcium leaching and chloride ingress

In addition to chemical attacks caused by deleterious substances penetrated into concrete, calcium ions would also leach out from the hydrated cement system in harsh environments [59]. The dissolution of calcium hydroxide and decalcification of C-S-H gel will lead to gradual coarsening of pore structure and increased porosity, which will then facilitate the ingress of other harmful species such as chloride ions [60]. Tang et al. [61] investigated the impact of calcium leaching on chloride diffusivities and they reported that the calcium leaching not only result in higher chloride diffusion rate but also reduce the chloride binding capacity. Recently, Zou et al. [62] both experimentally and numerically studied concrete leaching phenomenon when exposed to sulfate rich environments. It showed that sulfate ions could accelerate the leaching process of calcium. However, it should be noted that when considering calcium leaching and external solution, more than one ionic species would get involved, as shown in Fig. 7. As a result, the multi-ions coupling effect and the corresponding influence on calcium leaching should be considered. Based on the “double multi” model, the coupled calcium leaching and chloride ingress was numerically modelled [63], and it illustrated that the electrostatic potential induced by multi-ions coupling effect would firstly facilitate the leaching process and then slightly limit the calcium dissolution process.

3.4 Coupled deterioration of freeze-thaw and chloride ingress

For concrete structures constructed in middle and high latitude marine/deicing-salt environments, they are also susceptible to the combined attack of freeze-thaw and chloride ingress [64]. The damage caused by freeze-thaw action can be mainly reflected by cracks propagation facilitating the ingress of chloride ions and damage on concrete pore structures leading to a more connected pore network [65]. Moreover, under frost damage caused by ultra-low temperature, the C-S-H phase shows instability which also can lead to concrete mechanical degradation [66]. From the perspective of pore structure evolution, Li et al. [67] related the chloride diffusion coefficient to the freeze-thaw cycle numbers and proposed a coupling acceleration coefficient to quantitively characterize the acceleration effect on chloride penetration caused by freeze-thaw damage. By adopting a time-dependent variable of porosity, Jiang et al. [68] established a coupling model for the combined attack of freeze-thaw cycles and chloride penetration. Some interesting findings about the parametric analysis and chloride ingress prediction were also obtained by using Grey relational analysis and Bayesian updating [69], which brings insights into the durability prediction of existing structures under the action of multiple deterioration factors. Recently, as illustrated in Fig. 8, Li et al. further considered not only the FTC-induced cracking [70] but also the FTC-induced freezing [71], which couples the temperature variation, salt solution and time-dependent freezing rate, etc. It is found that although the larger salt concentration can reduce the freezing rate and temperature in pores, it still generally promotes chloride penetration.

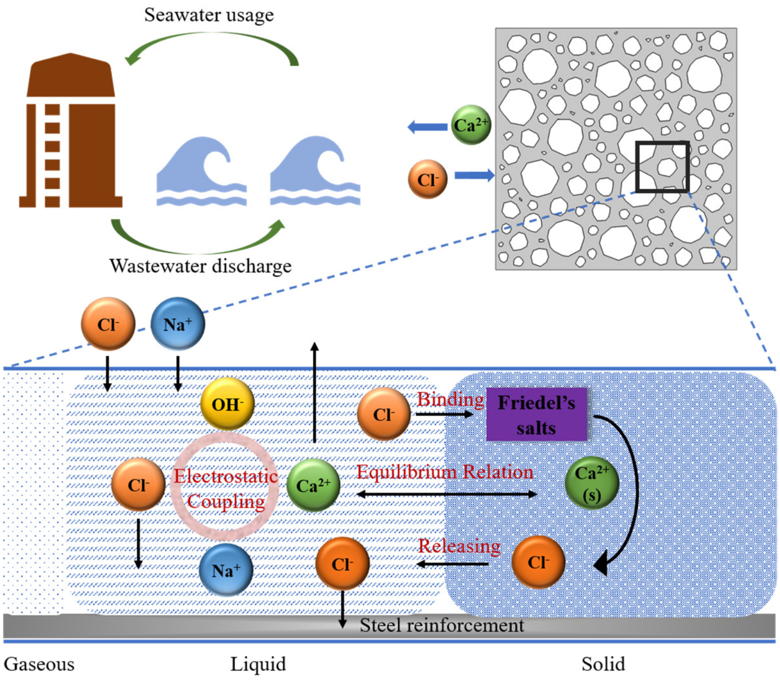

Figure 7. Schematic diagram of concrete suffering from both calcium leaching and chloride ingress. Adapted from [63].

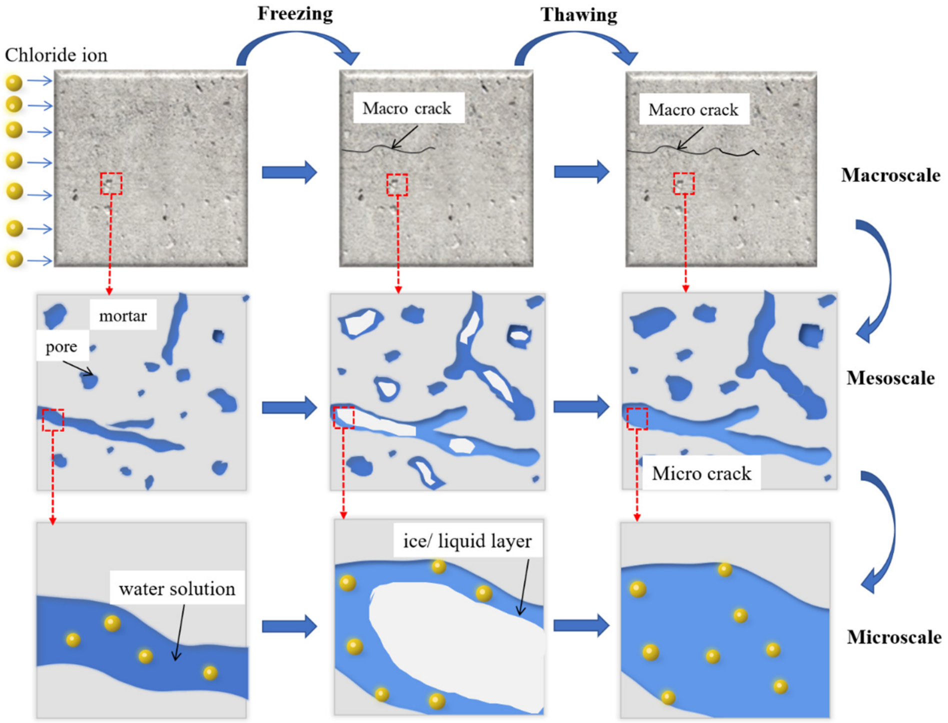

Figure 8. Schematic diagram of concrete damaged the dual attack of freeze-thaw cycles and chloride ingress. Adapted from [70, 71].

3.5 Coupled deterioration of external load and chloride ingress

Similarly, load-induced cracking will also provide convenient channels for the transport of chloride ions. Both experimental observation and numerical results indicate that the existence of cracks can introduce obvious deviations from the diffusion in sound concrete, and the promotion of cracks is dependent on the width and morphology [72]. Šavija et al. [73] proposed a lattice model to investigate the influence of cracks on chloride migration, and the results showed that under the application of an external electric field, the existence of cracks would cause a sharp increase in chloride penetration front. Most existing numerical models typically firstly simulated the cracking process and then adopted the cracks as the input of the subsequent chloride penetration simulation. However, it should be noted that concrete cracking and chloride ingress are both time-dependent processes that would appear on the same time scale, and the bidirectional coupling of the cracking process and chloride penetration is still quite challenging considering the modern computer science. This is because to actually couple the cracking with chloride ingress, the crack propagation process should be reflected on the geometric level which indicates a time-dependent model geometry, while the continuously changed geometry certainly will have a series of effects on the meshing quality and numerical convergency [74]. As a result, Liu et al. tried to divide this coupled process into several stages over time, and each stage is linked through a statistical learning method to achieve their internal coupling [75]. However, it has to be admitted that the coupling between crack propagation and chloride transport by statistical learning is still a compromise, and the prediction accuracy is highly dependent on the number of divided stages. Thus, more powerful and comprehensive modelling techniques on this aspect are expected in future research.

3.6 Advanced techniques for concrete durability prediction

Besides, thanks to the development of artificial intelligence technology, statistical analysis and machine learning techniques can also be applied to predict concrete durability [76]. For instance, statistical analysis has been adopted to predict chloride concentration in concrete exposed to offshore environments in literature [77]. By employing artificial neural network (ANN) techniques, Liu et al. [78] developed a model to predict the chloride diffusivity in concrete. It showed that the ANN is particularly powerful for predicting chloride resistance of concrete structures exposed to complex and harsh environments, and ANN has been proved to be an effective secondary tool to identify error information occurred in experimental measurement. Recently, Ashraf et al. [79] used gene expression programming (GEP) to predict both the mechanical and durability properties of sustainable concrete incorporating its economic and environmental factors. The more advanced multi-expression programming (MEP) method, as shown in Fig. 9, has also been utilized to model the properties of green concrete containing waste foundry sand, which can provide reliable engineering references and promote its application [80]. However, it can be seen that the application of artificial intelligence technology is still limited to single deterioration factor such as chloride penetration, and its application under the coupling of multiple factors still needs to be carried out in future studies.

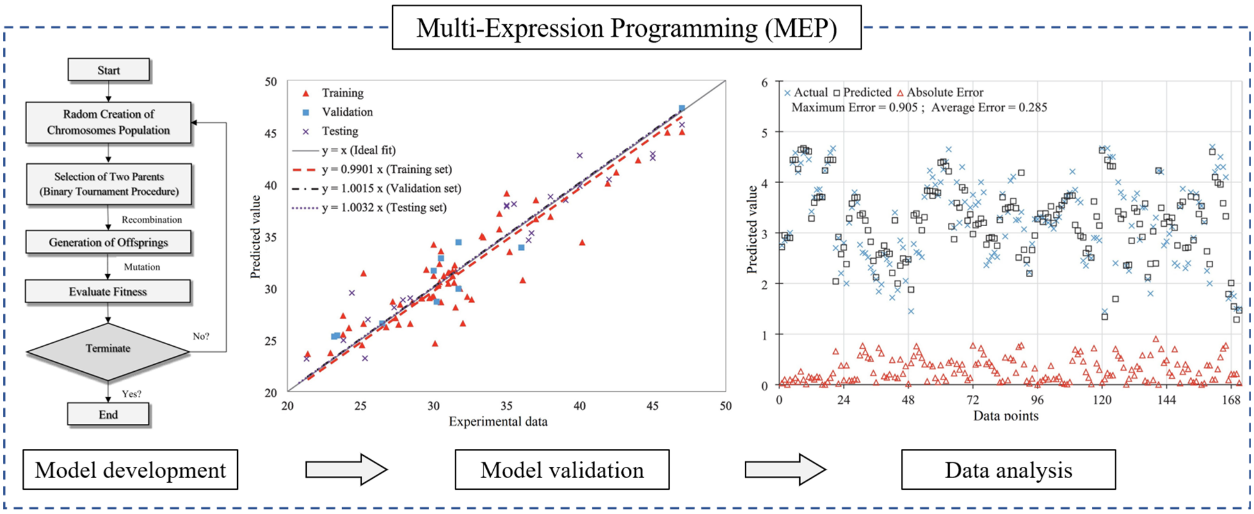

Figure 9. Use of multi-expression programming (MEP) to predict properties of green concrete containing waste foundry sand. Adapted from [80].

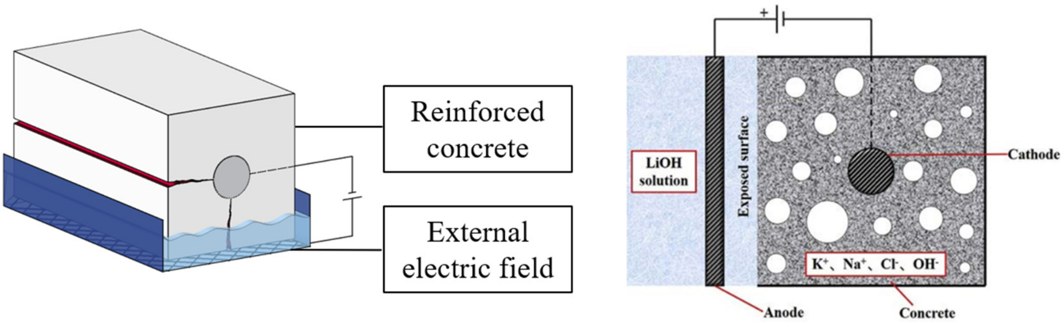

Figure 10. Schematic diagram of electrochemical deposition device for reinforced concrete structures. Adapted from [81, 82]

4 Electrochemical rehabilitations for RC structures

With a certain understanding of ion transport and various deterioration mechanisms in concrete, people may still have questions on when and how to properly apply electrochemical rehabilitation methods for RC structures which are about to suffer or have already suffered from durability degradation. The schematic arrangement for the electrochemical rehabilitation method is shown in Fig. 10. By applying current or voltage between the embedded reinforcement (acting as the cathode) and external metal mesh (acting as the anode), an electric field will be formed to remove deleterious ions, and migrate beneficial ions such as calcium and lithium ions into the concrete.

However, inaccurate settings of electrochemical parameters such as treatment duration and current density amplitude will result in negative effects on the RC structures. For instance, excessive long electrochemical treatment will cause local acidification of concrete cover and lead to calcium leaching in the vicinity of the anode area [83, 84]. Meanwhile, a large current density will also produce a large amount of hydroxyl ions and even lead to the hydrogen evolution reaction on the electrode surface. The excessive hydroxyl ions will cause alkali silica reaction [85] and the hydrogen evolution reaction will even result in the hydrogen embrittlement of steel reinforcement [86], which will both cause irreversible damage to the reinforced concrete. Consequently, it is necessary to determine the suitable electrochemical parameters for RC structures serving in complex environmental conditions.

4.1 Electrochemical chloride removal

Among the various electrochemical rehabilitation methods, the electrochemical chlorine removal/extraction (ECR/ECR) was first proposed and applied in practical engineering. Relevant studies show that the current density of 2 A/m^2 is more suitable for electrochemical chloride removal [87]. Some scholars have also proposed to provide an alternating power supply for electrochemical treatment. The results showed that this can not only reduce the cost but also improve the efficiency of chloride extraction [88]. By employing the “Double Multi” model, a prediction method has been proposed to measure the efficiency of electrochemical chloride removal, where the multi-species coupling in pore solution, chloride binding between liquid solution and solid hydrated cement phases, and electrochemical reaction on electrodes have been comprehensively taken into account [89]. Shi et al. [90] firstly developed a 3D model to simulate the electrochemical chloride removal process, and the effect of steel position and cracks was discussed. However, it still should be admitted that most of the existing numerical models for electrochemical chloride removal were built in two-dimension and even one-dimension due to the high nonlinearity introduced by the electric field and electrochemical reactions. As a result, upgrading from 2D models to 3D models would be another challenge.

4.2 Improved methods of electrochemical chlorine removal

On the basis of electrochemical chloride removal, other beneficial substances such as corrosion inhibitors and lithium ions can be migrated into concrete to further retard the negative effect such as steel corrosion, hydrogen embrittlement and alkali silica reaction. A novel durability repair strategy called bidirectional electromigration rehabilitation (BIEM) has been firstly proposed by Jin et al. and has received extensive interest due to its multiple advantages including chloride removal and mitigating corrosion [91, 92]. A recent study has also shown that adopting amine rust inhibitors (such as triethylenetetramine) can effectively inhibit hydrogen embrittlement of steel reinforcement through chemical inhibition, which further ensures the safety and efficiency of electrochemical treatment [93]. Meanwhile, the BIEM has also been applied on the emerging sea sand concrete structures in recent years, and was proved to be an effective method to improve the durability of sea sand concrete structures [94].

As for the potential risk of alkali silica reaction, due to the smaller ion radius of lithium, it can alter ASR reaction by producing a non-expansive gel and has been proved to be effective in mitigating ASR. Therefore, the electrochemical lithium migration (ELM) method has also been put in junction with electrochemical chloride removal for concrete affected by both ASR and chloride ingress, which is named as ELM-ECR by Liu's group, as shown in Fig. 11. Ueda et al. [95] investigated the influence of temperature on lithium migration and chloride removal, and proved that higher temperature was beneficial to the healing effect. Recently, as reported by Figueira et al's review article[96], Mao et al. [82] developed a numerical model to study the lithium impregnation and chloride removal efficiency, where the interaction between aggregates and lithium ions, chloride binding and the electrochemical reactions at electrodes have been comprehensively characterized, and influence factors including lithium concentration, current density and ambient temperature have been investigated through a detailed parametric study.

4.3 Electrochemical deposition method for crack healing

For reinforced concrete structures which have already been damaged, cracks may serve as a convenient channel for the penetration of harmful ions. Therefore, the electrochemical deposition method (EDM) has been proposed as a non-destructive and efficient approach to close cracks [97]. Besides, it is worth mentioning that in addition to crack closure, the electrochemical deposition method has multiple advantages in chloride removal and realkalization of previously corroded steel reinforcement, which brings the potential to repair multiple durability degradation problems of RC structures at the same time. As illustrated in Fig. 12, The basic principle of EDM is to migrate metal cations such as magnesium and zinc ions in the anolyte into concrete, which will react with the hydroxyl ions in pore solution as well as those generated at the electrode surface to precipitate hydroxide depositions. Subsequently, the deposition products will fill cracks and further densify concrete pore structure to prevent concrete from being eroded by harmful substances in remaining service life [98].

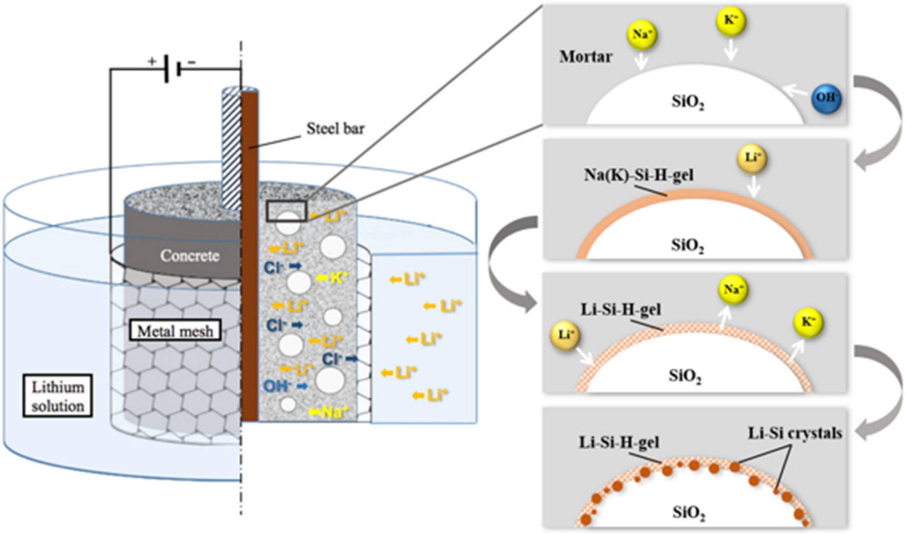

Figure 11. Schematic diagram of the mechanism of ELM-ECR method for ASR mitigation and chloride removal.

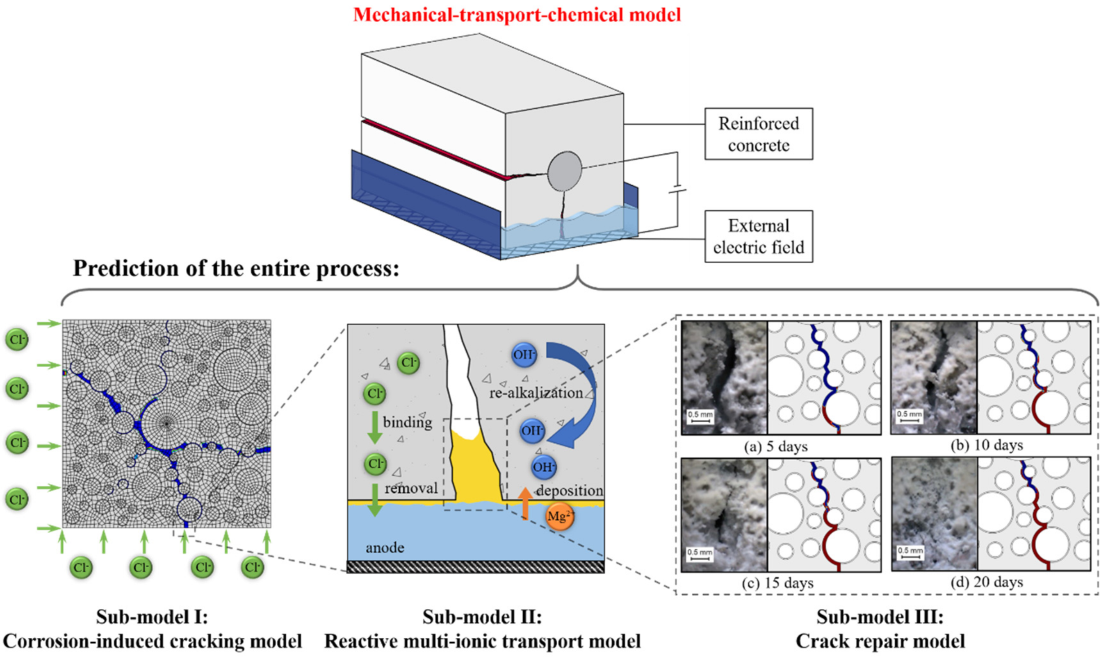

Figure 12. The schematic diagram for the mechanisms of the electrochemical deposition method. Adapted from [99].

A series of experimental studies on this promising electrochemical rehabilitation method have shown that higher current density, external electrolyte concentration and cation types will influence the crack closure rate, concrete chemical compositions, and even deposition morphology [100-102]. As for the aspect of numerical modelling, Zhou et al. developed a multiphysics model which can digitally visualize the deposition process in both electrode surface and concrete cracks. Meng et al. [81] developed a numerical model which covers the entire process from load-induced cracking to crack repair by electrochemical deposition treatment. Results showed that a larger current density would lead to a lower crack repair rate, which is because the rapidly formed deposition under a higher current density will block the subsequent supply of metal ions. Recently, a comprehensive mechanical–transport–chemical model has been proposed aiming at corrosion-induced cracks, and various influence factors have also been investigated [99]. Besides, considering that the ASR-induced crack distribution pattern is more discrete, the repair arrangement should be different from that applied for the aforementioned two cracking reasons. Numerical modelling results also confirmed that for ASR-damaged concrete, making all exposed surfaces as working anodes can ensure the optimal repair effect [103]. Through the above research, it can be seen that the electrochemical deposition method is also a powerful rehabilitation technique that can repair damage caused by a variety of concrete durability problems at the same time, but the detailed arrangement of the repair device and settings of electrochemical parameters during the treatment would still depend on the specific durability problem.

5 Concluding remarks

In recent decades, remarkable progress has been made in the field of ionic transport in concrete, concrete service life prediction, as well as effective rehabilitation strategies, which greatly facilitate the development of the concrete industry. This letter provides a review on major breakthroughs in these three closely related areas, and opportunities and challenges in numerical modelling of multi-species transport, concrete durability prediction and electrochemical rehabilitation can be summarized in the following aspects.

Firstly, there is still a large room for numerical models aiming at coupled durability deterioration to get further improvement. The bidirectional coupling between crack propagation and ionic transport also remains to be realized at the same time scale. Besides, the evolution of concrete pore structure and the porosity characterization under different durability diseases still need to more comprehensive exploration. The influence of crack propagation and pore structure damage on ionic transport, water transport, as well as percolation in cracks and ITZ also need to be digitally quantified through the numerical modelling approach. In addition, the involvement of environmental factors such as ambient temperature, humidity and weathering still need more accurate physical and mathematical expression.

Secondly, due to the high non-linearity introduced by multi-ionic coupling and chemical and electrochemical reactions between ionic species and hydrated cement phases, three-dimensional models which consider the interaction among various ionic species, intrinsic chemical and electrochemical reactions, as well as the heterogeneity nature of concrete are still limited. Optimization from the aspect of computer algorithms and innovative modelling techniques can potentially help to solve this technical problem. Also, with the development of computer-aided technology, advanced upgrading techniques would also be beneficial to upgrade the two-dimensional model to a more accurate and realistic three-dimensional one.

Thirdly, expansive research scope from larger structural components to micro particles, from early age to long-term performance would also help to better understand intrinsic mechanisms. Interpreting the macro phenomena observed in nature to the micro behaviours in theory has always been difficult, but a fundamental understanding of how these degradation processes occurred and their interactions would shed light on the development of accurate prediction and evaluation. In addition, one of the most important targets of durability studies is to support the life-cycle design of reinforced concrete structures to ensure service safety, so bridging the gap between microscopic durability degradation mechanisms the macroscopic structural mechanical performance also needs more attention. Meanwhile, relating the early-stage rheology properties to the ultimate deterioration phenomenon would also be another potential breakthrough to comprehensively evaluate the service life.

Lastly, current studies in this topic area mainly focus on the traditional concrete type, but with the rapid development and application of alkali activated cementitious material, high-performance concrete, and various types of sustainable/green concrete, the durability problems of these new-type concrete will gradually become prominent. However, due to the different chemical composition and preparation process compared to traditional concrete, the ionic transport, durability degradation and corresponding electrochemical repair technologies would possess distinctively new features which would be hard to predict through existing models. Therefore, carrying out research focusing on the durability mechanism of these new types of concrete should also receive considerable attention.

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References

[1] Ozbolt J, Balabanic G, Kuster M. 3D Numerical modelling of steel corrosion in concrete structures. Corros Sci. 2011;53:4166-77. https://doi.org/10.1016/j.corsci.2011.08.026

[2] Cai YX, Liu QF, Yu LW, Meng ZZ, Hu Z, Yuan Q et al. An experimental and numerical investigation of coarse aggregate settlement in fresh concrete under vibration. Cem Concr Comp. 2021;122:104153. https://doi.org/10.1016/j.cemconcomp.2021.104153

[3] Roziere E, Loukili A, El Hachem R, Grondin F. Durability of concrete exposed to leaching and external sulphate attacks. Cem Concr Res. 2009;39:1188-98. https://doi.org/10.1016/j.cemconres.2009.07.021

[4] Kamali S, Gerard B, Moranville M. Modelling the leaching kinetics of cement-based materials - influence of materials and environment. Cem Concr Comp. 2003;25:451-8. https://doi.org/10.1016/S0958-9465(02)00085-9

[5] Wang Y, Nanukuttan S, Bai Y, Basheer PAM. Influence of combined carbonation and chloride ingress regimes on rate of ingress and redistribution of chlorides in concretes. Constr Build Mater. 2017;140:173-83. https://doi.org/10.1016/j.conbuildmat.2017.02.121

[6] Planel D, Sercombe J, Le Bescop P, Adenot F, Torrenti JM. Long-term performance of cement paste during combined calcium leaching-sulfate attack: kinetics and size effect. Cem Concr Res. 2006;36:137-43. https://doi.org/10.1016/j.cemconres.2004.07.039

[7] Ma Y, Li W, Jin M, Liu J, Zhang J, Huang J et al. Influences of leaching on the composition, structure and morphology of calcium silicate hydrate (C-S-H) with different Ca/Si ratios. J Build Eng. 2022;58:105017. https://doi.org/10.1016/j.jobe.2022.105017

[8] Yang LF, Pathirage M, Su HZ, Alnaggar M, Di Luzio G, Cusatis G. Computational modeling of temperature and relative humidity effects on concrete expansion due to alkali-silica reaction. Cem Concr Comp. 2021;124:104237. https://doi.org/10.1016/j.cemconcomp.2021.104237

[9] Wang YZ, Liu Z, Fu K, Li QM, Wang YC. Experimental studies on the chloride ion permeability of concrete considering the effect of freeze-thaw damage. Constr Build Mater. 2020;236:117556. https://doi.org/10.1016/j.conbuildmat.2019.117556

[10] Jin L, Xu JD, Zhang RB, Du XL. Numerical study on the impact performances of reinforced concrete beams: A mesoscopic simulation method. Eng Fail Anal. 2017;80:141-63. https://doi.org/10.1016/j.engfailanal.2017.06.005

[11] Cai YX, Liu QF, Meng ZZ, Chen MZ, H. LW, B. S. Influence of coarse aggregate settlement induced by vibration on long-term chloride transport in concrete: a numerical study. Mater Struct. 2023. https://doi.org/10.1617/s11527-022-02038-z

[12] Cheng X, Xia J, Wu RJ, Jin WL, Pan CG. Optimisation of sacrificial anode cathodic protection system in chloride-contaminated reinforced concrete structure. J Build Eng. 2022;45:103515. https://doi.org/10.1016/j.jobe.2021.103515

[13] Bertolini L, Spagnolo SL, Redaelli E. Electrochemical Realkalization as a Conservation Technique for Reinforced Concrete. Int J Archit Herit. 2012;6:214-27. https://doi.org/10.1080/15583058.2010.528147

[14] Xu C, Jin WL, Wang HL, Wu HT, Huang N, Li ZY et al. Organic corrosion inhibitor of triethylenetetramine into chloride contamination concrete by eletro-injection method. Constr Build Mater. 2016;115:602-17. https://doi.org/10.1016/j.conbuildmat.2016.04.076

[15] Qiao GF, Guo BB, Ou JP, Xu F, Li ZH. Numerical optimization of an impressed current cathodic protection system for reinforced concrete structures. Constr Build Mater. 2016;119:260-7. https://doi.org/10.1016/j.conbuildmat.2016.05.012

[16] Guo BB, Qiao GF, Han P, Fu Q. Numerical study on effects of the degree of water saturation on ICCP of chloride-contaminated RC structures. J Build Eng. 2022;45:103619. https://doi.org/10.1016/j.jobe.2021.103619

[17] Hu Z, Mao LX, Xia J, Liu JB, Gao J, Yang J et al. Five-phase modelling for effective diffusion coefficient of chlorides in recycled concrete. Mag Concr Res. 2018;70:583-94. https://doi.org/10.1680/jmacr.17.00194

[18] Ren WY, Yang ZJ, Sharma R, Zhang C, Withers PJ. Two-dimensional X-ray CT image based meso-scale fracture modelling of concrete. Eng Fract Mech. 2015;133:24-39. https://doi.org/10.1016/j.engfracmech.2014.10.016

[19] Qiu QW, Dai JG. Meso-scale modeling of chloride diffusivity in mortar subjected to corrosion-induced cracking. Comput-Aided Civ Inf. 2021;36:602-19. https://doi.org/10.1111/mice.12657

[20] Carrara P, Kruse R, Bentz DP, Lunardelli M, Leusmann T, Varady PA et al. Improved mesoscale segmentation of concrete from 3D X-ray images using contrast enhancers. Cem Concr Comp. 2018;93:30-42. https://doi.org/10.1016/j.cemconcomp.2018.06.014

[21] Sheng PY, Chen ZT, Zhang JZ, Ji Z. Evolution and heredity of particle distribution in the free-fall method of modeling particle-reinforced concrete-like composites. Powder Technol. 2019;353:1-9. https://doi.org/10.1016/j.powtec.2019.04.083

[22] Wang ZM, Kwan AKH, Chan HC. Mesoscopic study of concrete I: generation of random aggregate structure and finite element mesh. Comput Struct. 1999;70:533-44. https://doi.org/10.1016/S0045-7949(98)00177-1

[23] Xu WX, Chen HS. Mesostructural characterization of particulate composites via a contact detection algorithm of ellipsoidal particles. Powder Technol. 2012;221:296-305. https://doi.org/10.1016/j.powtec.2012.01.016

[24] Zhang CH, Liu P, Li K, Shi CJ. Generation and property analyses of 3D mesoscale models for plain and fiber reinforced concretes. Cem Concr Comp. 2020;114:103714. https://doi.org/10.1016/j.cemconcomp.2020.103714

[25] Abyaneh SD, Wong HS, Buenfeld NR. Computational investigation of capillary absorption in concrete using a three-dimensional mesoscale approach. Comp Mater Sci. 2014;87:54-64. https://doi.org/10.1016/j.commatsci.2014.01.058

[26] Liu QF, Feng GL, Xia J, Yang J, Li LY. Ionic transport features in concrete composites containing various shaped aggregates: a numerical study. Compos Struct. 2018;183:371-80. https://doi.org/10.1016/j.compstruct.2017.03.088

[27] Liu L, Shen DJ, Chen HS, Xu WX. Aggregate shape effect on the diffusivity of mortar: A 3D numerical investigation by random packing models of ellipsoidal particles and of convex polyhedral particles. Comput Struct. 2014;144:40-51. https://doi.org/10.1016/j.compstruc.2014.07.022

[28] Li MQ, Chen HS, Lin JJ, Lura P, Zhu ZG. The bias of the interface thickness and diffusivity of concrete comprising Platonic aggregates induced by areal analysis. Powder Technol. 2020;376:209-21. https://doi.org/10.1016/j.powtec.2020.08.024

[29] Zheng JJ, Zhou XZ, Wu YF, Jin XY. A numerical method for the chloride diffusivity in concrete with aggregate shape effect. Constr Build Mater. 2012;31:151-6. https://doi.org/10.1016/j.conbuildmat.2011.12.061

[30] Yu L, Liu CH, Mei H, Xia Y, Liu Z, Xu F et al. Effects of aggregate and interface characteristics on chloride diffusion in concrete based on 3D random aggregate model. Constr Build Mater. 2022;314:125690. https://doi.org/10.1016/j.conbuildmat.2021.125690

[31] Elakneswaran Y, Iwasa A, Nawa T, Sato T, Kurumisawa K. Ion-cement hydrate interactions govern multi-ionic transport model for cementitious materials. Cem Concr Res. 2010;40:1756-65. https://doi.org/10.1016/j.cemconres.2010.08.019

[32] Guo BB, Hong Y, Qiao GF, Ou JP. A COMSOL-PHREEQC interface for modeling the multi-species transport of saturated cement-based materials. Constr Build Mater. 2018;187:839-53. https://doi.org/10.1016/j.conbuildmat.2018.07.242

[33] Snyder KA, Marchand J. Effect of speciation on the apparent diffusion coefficient in nonreactive porous systems. Cem Concr Res. 2001;31:1837-45. https://doi.org/10.1016/S0008-8846(01)00679-2

[34] Samson E, Marchand J, Snyder KA, Beaudoin JJ. Modeling ion and fluid transport in unsaturated cement systems in isothermal conditions. Cem Concr Res. 2005;35:141-53. https://doi.org/10.1016/j.cemconres.2004.07.016

[35] Samson E, Marchand J. Modeling the effect of temperature on ionic transport in cementitious materials. Cem Concr Res. 2007;37:455-68. https://doi.org/10.1016/j.cemconres.2006.11.008

[36] Samson E, Marchand J. Modeling the transport of ions in unsaturated cement-based materials. Comput Struct. 2007;85:1740-56. https://doi.org/10.1016/j.compstruc.2007.04.008

[37] Johannesson B, Yamada K, Nilsson LO, Hosokawa Y. Multi-species ionic diffusion in concrete with account to interaction between ions in the pore solution and the cement hydrates. Mater Struct. 2007;40:651-65. https://doi.org/10.1617/s11527-006-9176-y

[38] Liu QF, Easterbrook D, Yang J, Li LY. A three-phase, multi-component ionic transport model for simulation of chloride penetration in concrete. Eng Struct. 2015;86:122-33. https://doi.org/10.1016/j.engstruct.2014.12.043

[39] Liu QF, Li LY, Easterbrook D, Yang J. Multi-phase modelling of ionic transport in concrete when subjected to an externally applied electric field. Eng Struct. 2012;42:201-13. https://doi.org/10.1016/j.engstruct.2012.04.021

[40] Liu Q. Multi-Phase Modelling of Concrete at Meso-micro Scale Based on Multi-species Transport. Journal of the Chinese Ceramic Society. 2018;46:1074-80. https://doi.org/10.14062/j.issn.0454-5648.2018.08.05

[41] Liu QF, Yang J, Xia J, Easterbrook D, Li LY, Lu XY. A numerical study on chloride migration in cracked concrete using multi-component ionic transport models. Comp Mater Sci. 2015;99:396-416. https://doi.org/10.1016/j.commatsci.2015.01.013

[42] Chen W, Liu Q. Moisture and multi-ions transport in concrete under drying-wetting cycles: a numerical study. Journal of Hydraulic Engineering. 2021;52:622-32. https://doi.org/10.13243/j.cnki.slxb.20201099

[43] Feng GL, Li LY, Kim B, Liu QF. Multiphase modelling of ionic transport in cementitious materials with surface charges. Comp Mater Sci. 2016;111:339-49. https://doi.org/10.1016/j.commatsci.2015.09.060

[44] Savija B, Lukovic M. Carbonation of cement paste: Understanding, challenges, and opportunities. Constr Build Mater. 2016;117:285-301. https://doi.org/10.1016/j.conbuildmat.2016.04.138

[45] Houst YF, Wittmann FH. Depth profiles of carbonates formed during natural carbonation. Cem Concr Res. 2002;32:1923-30. https://doi.org/10.1016/S0008-8846(02)00908-0

[46] Suryavanshi AK, Narayan Swamy R. Stability of Friedel's salt in carbonated concrete structural elements. Cem Concr Res. 1996;26:729-41. https://doi.org/10.1016/S0008-8846(96)85010-1

[47] Shen XH, Liu QF, Hu Z, Jiang WQ, Lin XS, Hou DS et al. Combine ingress of chloride and carbonation in marine-exposed concrete under unsaturated environment: A numerical study. Ocean Eng. 2019;189:106350. https://doi.org/10.1016/j.oceaneng.2019.106350

[48] Rimmele G, Barlet-Gouedard V, Porcherie O, Goffe B, Brunet F. Heterogeneous porosity distribution in Portland cement exposed to CO_2-rich fluids. Cem Concr Res. 2008;38:1038-48. https://doi.org/10.1016/j.cemconres.2008.03.022

[49] Saetta AV, Schrefler BA, Vitaliani RV. The carbonation of concrete and the mechanism of moisture, heat and carbon dioxide flow through porous materials. Cem Concr Res. 1993;23:761-72. https://doi.org/10.1016/0008-8846(93)90030-D

[50] Geng J, Easterbrook D, Liu QF, Li LY. Effect of carbonation on release of bound chlorides in chloride-contaminated concrete. Mag Concr Res. 2016;68:353-63. https://doi.org/10.1680/jmacr.15.00234

[51] Shen XH, Jiang WQ, Hou DS, Hu Z, Yang J, Liu QF. Numerical study of carbonation and its effect on chloride binding in concrete. Cem Concr Comp. 2019;104:103402. https://doi.org/10.1016/j.cemconcomp.2019.103402

[52] Chen Z, Yu J, Bindiganavile V, Yi C, Shi C, Hu X. Time and spatially dependent transient competitive antagonism during the 2-D diffusion-reaction of combined chloride-sulphate attack upon concrete. Cem Concr Res. 2022;154:106724. https://doi.org/10.1016/j.cemconres.2022.106724

[53] Zuquan J, Wei S, Yunsheng Z, Jinyang J, Jianzhong L. Interaction between sulfate and chloride solution attack of concretes with and without fly ash. Cem Concr Res. 2007;37:1223-32. https://doi.org/10.1016/j.cemconres.2007.02.016

[54] Ikumi T, Segura I. Numerical assessment of external sulfate attack in concrete structures. A review. Cem Concr Res. 2019;121:91-105. https://doi.org/10.1016/j.cemconres.2019.04.010

[55] Wang PG, Mo R, Li S, Xu J, Jin ZQ, Zhao TJ et al. A chemo-damage-transport model for chloride ions diffusion n cement-based materials: Combined effects of sulfate attack and temperature. Constr Build Mater. 2021;288:123121. https://doi.org/10.1016/j.conbuildmat.2021.123121

[56] Yu YG, Gao W, Feng Y, Castel A, Chen XJ, Liu AR. On the competitive antagonism effect in combined chloride-sulfate attack: A numerical exploration. Cem Concr Res. 2021;144:106406. https://doi.org/10.1016/j.cemconres.2021.106406

[57] Chen Z, Wu LY, Bindiganavile V, Yi CF. Coupled models to describe the combined diffusion-reaction behaviour of chloride and sulphate ions in cement-based systems. Constr Build Mater. 2020;243:118232. https://doi.org/10.1016/j.conbuildmat.2020.118232

[58] Zhang CL, Chen WK, Mu S, Savija B, Liu QF. Numerical investigation of external sulfate attack and its effect on chloride binding and diffusion in concrete. Constr Build Mater. 2021;285:122806. https://doi.org/10.1016/j.conbuildmat.2021.122806

[59] de Larrard T, Benboudjema F, Colliat JB, Torrenti JM, Deleruyelle F. Concrete calcium leaching at variable temperature: Experimental data and numerical model inverse identification. Comp Mater Sci. 2010;49:35-45. https://doi.org/10.1016/j.commatsci.2010.04.017

[60] Wang Y, Yuan Q, Deng DH. Modelling calcium leaching kinetics of cement asphalt paste. Mater Struct. 2018;51. https://doi.org/10.1617/s11527-018-1261-5

[61] Tang YJ, Zuo XB, Yin GJ, Davoudi H, Li XN. Influence of calcium leaching on chloride diffusivity in cement-based materials. Constr Build Mater. 2018;174:310-9. https://doi.org/10.1016/j.conbuildmat.2018.04.112

[62] Zou D, Zhang M, Qin S, Liu T, Tong W, Zhou A et al. Calcium leaching from cement hydrates exposed to sodium sulfate solutions. Constr Build Mater. 2022;351:128975. https://doi.org/10.1016/j.conbuildmat.2022.128975

[63] Liu QF, Shen XH, Savija B, Meng ZZ, Tsang DCW, Sepasgozar S et al. Numerical study of interactive ingress of calcium leaching, chloride transport and multi-ions coupling in concrete. Cement Concrete Res. 2022.

[64] Kessler S, Thiel C, Grosse CU, Gehlen C. Effect of freeze-thaw damage on chloride ingress into concrete. Mater Struct. 2017;50:121. https://doi.org/10.1617/s11527-016-0984-4

[65] Wang L, Ueda T. Mesoscopic simulation of chloride ions diffusion in frost-damaged concrete. International Journal of Modelling, Identification and Control. 2009;7:148-54. https://doi.org/10.1504/IJMIC.2009.027068

[66] Zhu XP, Ren Q, He B, Zhang HE, Jiang ZW. Upscaling degradation of cementitious calcium (aluminate) silicate hydrate upon ultra-low temperature attack: A multiscale insight and a bottom-up enhancement route. Compos Part B-Eng. 2022;243:110122. https://doi.org/10.1016/j.compositesb.2022.110122

[67] Li B, Mao JZ, Nawa T, Liu ZM. Mesoscopic chloride ion diffusion model of marine concrete subjected to freeze-thaw cycles. Constr Build Mater. 2016;125:337-51. https://doi.org/10.1016/j.conbuildmat.2016.08.052

[68] Jiang WQ, Shen XH, Xia J, Mao LX, Yang J, Liu QF. A numerical study on chloride diffusion in freeze-thaw affected concrete. Constr Build Mater. 2018;179:553-65. https://doi.org/10.1016/j.conbuildmat.2018.05.209

[69] Jiang WQ, Shen XH, Hong SX, Wu ZY, Liu QF. Binding capacity and diffusivity of concrete subjected to freeze-thaw and chloride attack: A numerical study. Ocean Eng. 2019;186:106093. https://doi.org/10.1016/j.oceaneng.2019.05.075

[70] Li LJ, Liu QF, Tang LP, Hu Z, Wen Y, Zhang P. Chloride penetration in freeze-thaw induced cracking concrete: A numerical study. Constr Build Mater. 2021;302:124291. https://doi.org/10.1016/j.conbuildmat.2021.124291

[71] Li LJ, Liu QF. Freezing Rate and Chloride Transport in Concrete Subjected to Freeze-Thaw Cycles: A Numerical Study. Journal of the Chinese Ceramic Society. 2022:1-12. https://doi.org/10.14062/j.issn.0454-5648.20211102

[72] Savija B, Pacheco J, Schlangen E. Lattice modeling of chloride diffusion in sound and cracked concrete. Cem Concr Comp. 2013;42:30-40. https://doi.org/10.1016/j.cemconcomp.2013.05.003

[73] Savija B, Lukovic M, Schlangen E. Lattice modeling of rapid chloride migration in concrete. Cem Concr Res. 2014;61-62:49-63. https://doi.org/10.1016/j.cemconres.2014.04.004

[74] Peng C, Wu Q, Shen J, Mo R, Xu J. Numerical study on the effect of transverse crack self-healing on the corrosion rate of steel bar in concrete. J Build Eng. 2021;41:102767. https://doi.org/10.1016/j.jobe.2021.102767

[75] Liu QF, Hu Z, Wang XE, Zhao HT, Qian K, Li LJ et al. Numerical study on cracking and its effect on chloride transport in concrete subjected to external load. Constr Build Mater. 2022;325:126797. https://doi.org/10.1016/j.conbuildmat.2022.126797

[76] Zhang J, Zhang M, Dong B, Ma H. Quantitative evaluation of steel corrosion induced deterioration in rubber concrete by integrating ultrasonic testing, machine learning and mesoscale simulation. Cem Concr Compos. 2022;128:104426. https://doi.org/10.1016/j.cemconcomp.2022.104426

[77] Liu QF, Hu Z, Lu XY, Yang J, Azim I, Sun WZ. Prediction of Chloride Distribution for Offshore Concrete Based on Statistical Analysis. Materials. 2020;13:174. https://doi.org/10.3390/ma13010174

[78] Liu QF, Iqbal MF, Yang J, Lu XY, Zhang P, Rauf M. Prediction of chloride diffusivity in concrete using artificial neural network: Modelling and performance evaluation. Constr Build Mater. 2021;268:121082. https://doi.org/10.1016/j.conbuildmat.2020.121082

[79] Ashraf M, Iqbal MF, Rauf M, Ashraf MU, Ulhaq A, Muhammad H et al. Developing a sustainable concrete incorporating bentonite clay and silica fume: Mechanical and durability performance. Journal of Cleaner Production. 2022;337:130315. https://doi.org/10.1016/j.jclepro.2021.130315

[80] Iqbal MF, Javed MF, Rauf M, Azim I, Ashraf M, Yang J et al. Sustainable utilization of foundry waste: Forecasting mechanical properties of foundry sand based concrete using multi-expression programming. Sci Total Environ. 2021;780:146524. https://doi.org/10.1016/j.scitotenv.2021.146524

[81] Meng ZZ, Liu QF, She W, Cai YX, Yang J, Iqbal MF. Electrochemical deposition method for load-induced crack repair of reinforced concrete structures: A numerical study. Eng Struct. 2021;246:112903. https://doi.org/10.1016/j.engstruct.2021.112903

[82] Mao LX, Hu Z, Xia J, Feng GL, Azim I, Yang J et al. Multi-phase modelling of electrochemical rehabilitation for ASR and chloride affected concrete composites. Compos Struct. 2019;207:176-89. https://doi.org/10.1016/j.compstruct.2018.09.063

[83] Zhu JH, Wu XY, Mohamed IMA, Xing F. Electrochemical and microstructural evaluation of acidification damage induced by impressed current cathodic protection after incorporating a hydroxy activated-Mg/Al-double oxide in the external anode mortar. Constr Build Mater. 2021;309:125116. https://doi.org/10.1016/j.conbuildmat.2021.125116

[84] Cherif R, Hamami AE, Ait-Mokhtar A. Effects of leaching and chloride migration on the microstructure and pore solution of blended cement pastes during a migration test. Constr Build Mater. 2020;240:117934. https://doi.org/10.1016/j.conbuildmat.2019.117934

[85] Miranda JM, Gonzalez JA, Cobo A, Otero E. Several questions about electrochemical rehabilitation methods for reinforced concrete structures. Corros Sci. 2006;48:2172-88. https://doi.org/10.1016/j.corsci.2005.08.014

[86] Guo BB, Qiao GF, Li ZM, Li DS, Dai JH, Wang Y. Impressed current cathodic protection of chloride-contaminated RC structures with cracking: A numerical study. J Build Eng. 2021;44:102943. https://doi.org/10.1016/j.jobe.2021.102943

[87] Lin H, Li Y, Li YQ. A study on the deterioration of interfacial bonding properties of chloride-contaminated reinforced concrete after electrochemical chloride extraction treatment. Constr Build Mater. 2019;197:228-40. https://doi.org/10.1016/j.conbuildmat.2018.11.196

[88] Elsener B, Angst U. Mechanism of electrochemical chloride removal. Corros Sci. 2007;49:4504-22. https://doi.org/10.1016/j.corsci.2007.05.019

[89] Liu QF, Xia J, Easterbrook D, Yang J, Li LY. Three-phase modelling of electrochemical chloride removal from corroded steel-reinforced concrete. Constr Build Mater. 2014;70:410-27. https://doi.org/10.1016/j.conbuildmat.2014.08.003

[90] Liu YJ, Shi XM. Ionic transport in cementitious materials under an externally applied electric field: Finite element modeling. Constr Build Mater. 2012;27:450-60. https://doi.org/10.1016/j.conbuildmat.2011.07.019

[91] Fan WJ, Mao JH, Jin WL, Xia J, Zhang J, Li Q. Repair effect of bidirectional electromigration rehabilitation on concrete structures at different durability deterioration stages. Constr Build Mater. 2020;251:118872. https://doi.org/10.1016/j.conbuildmat.2020.118872

[92] Pan CG, Mao JH, Jin WL, Fan WJ, Zhu DY. Effects of environmental Water-Level changes and bidirectional electromigration rehabilitation on durability of concrete. Constr Build Mater. 2020;265:120335. https://doi.org/10.1016/j.conbuildmat.2020.120335

[93] Xie Z, Jin W, Mao J, Zhang J, Fan W, Xia J. Variation and Impact of Hydrogen Content of Reinforcing Bars in Concrete Caused by Bidirectional Electromigration. Materials Review. 2020;34:2039-45. https://doi.org/10.11896/cldb.18120112

[94] Mao J, Jin W, Zhang H, Xu C, Xia J. Technology for Enhancing Durability of Structures of Sea-sand Concrete and Its Application. J Chin Soc Corro. Prot (China). 2015;35:563-70. https://doi.org/10.11902/1005.4537.2014.123

[95] Ueda T, Kushida J, Tsukagoshi M, Nanasawa A. Influence of temperature on electrochemical remedial measures and complex deterioration due to chloride attack and ASR. Constr Build Mater. 2014;67:81-7. https://doi.org/10.1016/j.conbuildmat.2013.10.020

[96] Figueira RB, Sousa R, Coelho L, Azenha M, de Almeida JM, Jorge PAS et al. Alkali-silica reaction in concrete: Mechanisms, mitigation and test methods. Constr Build Mater. 2019;222:903-31. https://doi.org/10.1016/j.conbuildmat.2019.07.230

[97] Otsuki N, Ryu JS. Use of electrodeposition for repair of concrete with shrinkage cracks. J Mater Civil Eng. 2001;13:136-42. https://doi.org/10.1061/(ASCE)0899-1561(2001)13:2(136)

[98] Ryu JS, Otsuki N. Crack closure of reinforced concrete by electrodeposition technique. Cement Concrete Res. 2002;32:159-64. https://doi.org/10.1016/S0008-8846(01)00650-0

[99] Meng ZZ, Liu QF, Xia J, Cai YX, Zhu XJ, Zhou Y et al. Mechanical-transport-chemical modeling of electrochemical repair methods for corrosion-induced cracking in marine concrete. Comput-Aided Civ Inf. 2022; 276. https://doi.org/10.1111/mice.12827

[100] Chu HQ, Jiang LH, Xiong CS, You LS, Xu N. Use of electrochemical method for repair of concrete cracks. Constr Build Mater. 2014;73:58-66. https://doi.org/10.1016/j.conbuildmat.2014.09.031

[101] Chu HQ, Jiang LH, Song ZJ, Xu Y, Zhao SJ, Xiong CS. Repair of concrete crack by pulse electro-deposition technique. Constr Build Mater. 2017;148:241-8. https://doi.org/10.1016/j.conbuildmat.2017.05.033

[102] Chu HQ, Liang YC, Guo MZ, Zhu ZY, Zhao SJ, Song ZJ et al. Effect of electro-deposition on repair of cracks in reinforced concrete. Constr Build Mater. 2020;238:117725. https://doi.org/10.1016/j.conbuildmat.2019.117725

[103] Liu QF, Meng ZZ, Hou DS, Zhou Y, Cai YX, Zhang MZ et al. Numerical modelling of electrochemical deposition techniques for healing concrete damaged by alkali silica reaction. Eng Fract Mech. 2022:108765; 37:1854–1874. https://doi.org/10.1016/j.engfracmech.2022.108765