Repair of Flexurally Cracked Concrete Beams under Sustained Loading via a MICP Diffusion Method

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Abstract: - Most studies on microbially induced calcium carbonate precipitation (MICP) for concrete crack repair focus on unloaded members, while cracks in service are commonly subjected to sustained loading. This study proposes a diffusion-based MICP method for flexurally cracked concrete beams under sustained loading and compares it with a conventional injection method used for unloaded specimens. Five reinforced concrete beams were prepared and evaluated through chloride resistance tests and microstructural analysis. The results show that the diffusion method can effectively seal working cracks and reduce the apparent chloride diffusion coefficient by 54.75% compared with unrepaired specimens. Its durability improvement is comparable to that of the injection method, indicating good potential for engineering applications.

Key-Words: - MICP, Concrete beam, flexural crack, sustained loading, diffusion-based repair, chloride resistance, durability.

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1 Introduction

Though concrete material has very good compressive strength, its tensile strength is so low that it can easily crack under external loading, reducing the durability of reinforced concrete structures, [1]. – In recent years, a new type of remediation technology that was environmentally friendly, Microbially Induced Calcium Carbonate Precipitate (MICP) has been widely investigated. Owing to the simplicity and controllable features of the reaction process in urea hydrolysis, the latter is treated as a typical mechanism for crack remediation of MICP technology. For example, the ureolytic *Sporosarcina pasteurii* DSM 33 catalyses the hydrolysis of urea to ammonia and carbon dioxide. The increasing ammonia accumulation raises the pH level of the medium, facilitating the catalytic conversion of CO_2 to carbonate ions CO_3^{2-}. These ions subsequently combine with the calcium ions Ca^{2+} to produce calcium carbonate, $CaCO_3$ which fills and eventually closes the cracks, [2], [3], [4]. Studies have shown that this approach is not only capable of the successful crack filling and sealing, but also provides reinforcement to the concrete for otherwise weak materials and increases the erosion resistance as well by increasing their density, [3]. At present, research on MICP for the repair of concrete cracks has achieved remarkable progress at home and abroad. The main repair methods (Figure 1, Appendix) are injection, impregnation, spraying, and self-healing, [3], [5]. Injection process: An injection device is required in this method to force the repair solution into the crack interior; however, it is difficult to maintain the pressure, which prevents a more complicated retention procedure for the repair solute, [6]. With the support geotextile fabric under concrete samples without any loads to increase retention time, the through crack was repaired successfully after 12 days, [7]. The immersion process, which immerses entire components in the repair solution to infill cracks, is, however, limited in terms of operating conditions and component size, and it is therefore not viable for stressed structures. For instance, Reference [6] reported that sixteen samples of 45 mm diameter and 40 mm high were immersed and repaired in an unloaded condition. Non-through intermittent cracks were exclusively healed after 24 days. The spraying process has the virtue of easy operation, but poor penetration ability, and can only be used for treating surface soil, [8]. For the spray repair treatment performed on irregular cracks of 0.1–0.25 mm under an unloaded condition, some residual cracking was still evident after 56 days. But the self-healing process needs a bacterial solution to be included in concrete as it is mixed, [2]. Once there is a crack, the bacteria can be made to mineralise by water and achieve automatic healing.

This method is easy to use, but [9] found that the bacteria in microorganisms die out gradually in the concrete over a long period of time, and the repair effectiveness decreases. In a word, while it can be effective to repair cracks in certain conditions, it does not have systematic research in actual engineering applications, especially in construction crack repair under sustained loading.

The study on MICP crack repair has mainly been conducted on unloaded scenarios, and the consideration of the repair under sustained loading service was less addressed in reality engineering applications. This study employs an ion diffusion-based MICP repair method (hereafter referred to as the "diffusion method") to repair cracked beams under sustained loading conditions, as shown in Figure 2 (Appendix). Based on this, this paper systematically compares the crack repair performance of the diffusion method and the traditional injection method under different working conditions. By integrating macro-durability indicators and micro-characteristics, it evaluates their applicability and advantages in actual engineering environments.

2 Materials and Methods

2.1 Materials and Specimen Design

Ordinary Portland cement (P.O. 42.5 Grade) was used as the binder. The coarse aggregate consisted of crushed stone (5-31.5 mm particle size), while the fine aggregate was medium sand with a fineness modulus of 2.7. The concrete was designed for a target strength grade of C30, with a mix proportion (cement: sand: gravel: water) of 449:615:1116:220 by mass. The measured 28-day compressive strength was 33.3 MPa.

The test consisted of five reinforced concrete beams, including one intact reference beam (RB), two cracked beams without loading (C-UL), and two cracked beams under loading (C-SL). Specific details are shown in Table 1 (Appendix). Cracks were induced in all four cracked beams using a four-point bending method (Figure 3a, Appendix). After crack formation, the width of the primary crack was measured incrementally along the beam height from the crack base, and the average crack width was obtained through a multi-point measurement technique.

2.2 Repair Protocol

The bacterial strain used in the experiment was *S. pasteurii*. The medium composition included 20 g/L yeast extract, 15 g/L ammonium chloride, and 0.1 mmol/L nickel chloride ($NiCl_2$). The inoculum-to-medium ratio was 1:1000 by volume. Following inoculation, the bacterial suspension was incubated in a constant-temperature shaking incubator for 48 hours to obtain an active bacterial culture. The gelation solution was prepared by mixing 1 mol/L calcium acetate solution and 1 mol/L urea solution in a 1:1 volume ratio. The specific remediation method is as follows:

1) For the unloaded beam (C-UL-R), concrete cylindrical specimens with a diameter of 100 mm and a thickness of 50 mm were extracted from the crack location via core drilling. The cylindrical specimens were repaired using the injection method (Table 1 and Figure 3b in Appendix), with bacterial solution and cementitious solution injected twice daily for 17 consecutive days. After injection completion, the specimens were cured for 10 days in a mixture of cementitious solution and water at a 1:10 ratio.

2) For the Sustained Loading beam (C-SL-R), the diffusion method was used to repair the beam directly. Repairing the beam was accomplished by dripping the bacterial solution into the cracks, and a sponge absorbed the bonding solution. The repair was achieved through the continuous diffusion of the solution within the cracks, as shown in Figure 3b (Appendix). Over 10 days, the bacterial and bonding solutions were replenished daily to ensure ongoing repair.

2.3 Evaluation of Repair Effectiveness

After the repair of the crack, a chloride ion permeability test was carried out for the repaired specimen and the original cracked specimen to identify the resistance of chloride ion on concrete before and after MICP treatment crack repair. The test method is shown in Figure 3c (Appendix).

1) Carry out Rapid Chloride Migration (RCM) test to check the effect of repair by using the chloride migration coefficients [10] of cylindrical test pieces taken from the unloaded beams.

2) For the reference beam and sustained loading beam, perform a chloride salt dry-wet cycle. Choose the side of the cracked repair, without-repaired surface, and the beam reference specimen side as the eroding surface. RCT is then carried out to estimate the distribution of free chloride ions at different depths in the concrete [11], and from it, the chloride ion diffusion coefficient is obtained to determine the effectiveness

2.4 Microscopic Characterisation

For the characterisation of internal deposits deposited into cracks during the MICP remediation process, we carried out a microscopic examination with scanning electron microscopy (SEM) and X-ray diffraction (XRD) test according to the result of the macroscopic performance test. After repairing the vertical bending cracks on the cracked beam, we observed many white precipitates at about 0–10 mm below the crack from the erosion surface. We further examined the deposits by SEM and XRD. After repairing the unloaded specimen, the fractured samples were collected from the surface and inspected with SEM. Such a comprehensive microexamination also showed the differences in the crack-filling effectiveness of injection and diffusion methods at the micro level.

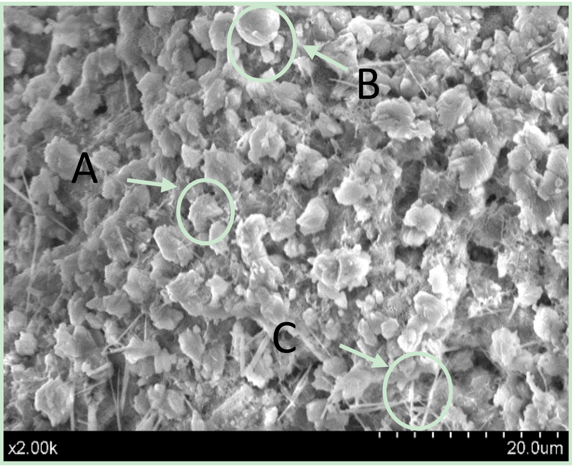

Fig. 4: SEM morphology of the precipitation products within injection-repaired cracks
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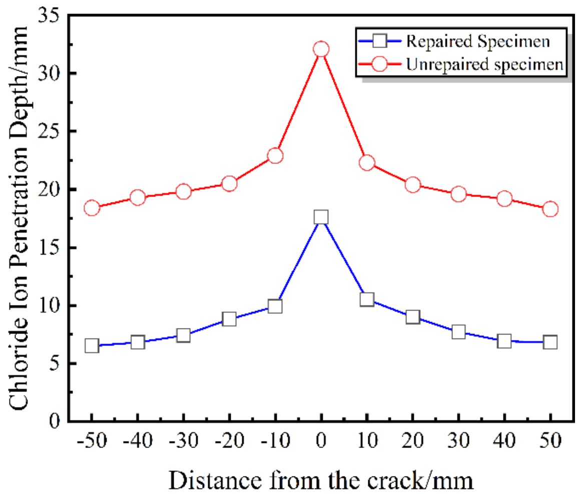

Fig. 5: Chloride ion penetration profiles at the crack location in unloaded specimens
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3 Results and Discussion

3.1 Evaluation on Crack Repair Effects of Unloaded Beams Obtained by the Injection Method For Concrete Cracks

3.1.1 Cylinder Visual-Repair Ability and Analysis of Repair Products

After injection, repair, and curing, the specimen surfaces were observed visually, and in the crack area, a white calcium carbonate deposit sealed this area like a relatively continuous cap. The SEM morphology of the crack repair area is shown in Figure 4. Deposits in the cracks are divided into three types of morphology: A, rhombohedral aggregate; B, spherical aggregate; C, acicular aggregate. Types A and B are usually very dense in clusters and contribute to the denseness of the concrete matrix.

3.1.2 Test of Chloride Ion Resistance Performance based on RCM Method

For the two types of specimens without post-cracking loading, the chloride ion penetration depth at the location of the crack was obtained with the RCM test, and the results are shown in Figure 5. At the location of the crack, chloride ion penetration in the concrete was most abundant. Compared with those without repairs, we found a significant reduction in the penetration depth of chloride ions in the repaired specimens, suggesting that the deposits closed the cracks, thus preventing chloride ions from penetrating. According to the Standard Test Methods for Long-Term Performance and Durability of Concrete (GB/T 30022-2013), the chloride ion migration coefficient D_{RCM} was obtained from equation (1):

$$D_{\mathrm{RCM}} = \frac{0.0239(273+T)L}{(U-2)t}\left(X_d - 0.0238\sqrt{\frac{(273+T)LX_d}{U-2}}\right) \quad (1)$$

where D_{RCM} is the non-steady-state chloride migration coefficient (m²/s), U is the absolute value of the applied voltage (V), T is the average temperature of the anode solution (°C), L is the specimen thickness (m), X_d Is the chloride penetration depth (m), and t is the test duration (s). 0238 comes from a combination of physical constants expressed as RT/ZFE, RT being the gas constant, Z being the ion charge number, and FE being the Faraday constant. Under normal test conditions, these combined constants implicitly have units that ensure the parameters on the right-hand side of an equation, such as U and t, produce a final value in units of m^2/s after calculation.

Reliability of the coefficient of migration of chloride ions in the electrolyte was confirmed using an error propagation analysis. Because it was derived from several independent variables (for example, voltage, temperature, specimen thickness, penetration depth), the synthetic standard uncertainty was calculated by the law of error propagation. Uncertainty of specimen thickness (in this study, take the dimensional tolerance of high-precision moulds as the basis) and penetration depth (depending on the measurement resolution of digital callipers) were. Calculations showed that the relative uncertainty of all values was less than 6.5% (Equation 2). Thus, the measured 54.75% reduction in the diffusion of chloride ion greatly exceeds the experimental error, which verifies the robustness of our conclusion.

$$\frac{u_c(D)}{D} = \sqrt{\left(\frac{u(L)}{L}\right)^2 + \left(\frac{u(X_d)}{X_d}\right)^2 + \left(\frac{u(U)}{U}\right)^2 + \left(\frac{u(T)}{T}\right)^2} \quad (2)$$

According to the calculation results, the chloride ion diffusion coefficient at the crack site after injection repair decreased to $6.5(\pm 0.4) \times 10^{-12}\ \mathrm{m}^2/s$, about 57.5% smaller than the unrepaired sample $15.3(\pm 1.0) \times 10^{-12}\ \mathrm{m}^2/\mathrm{s}$. The results of References [12] and [13] claimed that there was a drop of approximately 51% and 60% in the chloride diffusion coefficients by self-healing and spraying methods, respectively. Similarly, the injection method can also improve the resistance of concrete to chloride ion penetration.

3.2 Effect Evaluation of the Crack-Bearing Beam Diffusion Method of Repairing Concrete Cracks

3.2.1 Beam Visual Repair Capability and Micro-Product Analysis

During the crack diffusion repair process, observations from a section going along the crack height (vertical direction) showed that calcium carbonate deposition occurred on cracks according to a "bottom-up" pattern. Look for precipitation to occur at the bottom of a crack and spread upward until the entire channel is covered. Repair of vertical cracks showed a peculiar deposit stacking sequence, indicating that gravity is essential for the bottom-up formation of calcium carbonate layers.

Figure 6 (Appendix) shows the microscopic images of the white deposits. SEM images of the deposits show the deposits composed of a huge aggregate of spherical balls (Figure 6a, Appendix). Combined with the XRD results in Figure 6b (Appendix), this proof can also show that the repair product was mainly spherical vaterite and has a few contents of calcite.

3.2.2 Evaluation of Chloride Ion Resistance under Wet and Dry Cycles

Although these specimens underwent wet–dry cycling, the apparent diffusion coefficient of the chloride is evaluated based on Fick's second law. This is in agreement with the method applied by Reference [11], which showed that the complex transport processes occurring under cyclic conditions in a long term exposure experiment can be represented with equivalent diffusion models. Doing so also allows simple comparisons of repair performance in different types of remediation groups. When concrete is in a saturated state, the primary transport mechanism for chloride ions is generally considered to be diffusion, whose diffusion coefficient can be determined using Fick's Second Law. The diffusion model for the free chloride ion concentration distribution in concrete can be expressed by Equation (3):

$$C_\mathrm{f}(x,t) = C_\mathrm{s}\left[1 - \mathrm{erf}\left(\frac{x}{2\sqrt{D_\mathrm{a}t}}\right)\right] \quad (3)$$

where$C_f(x,t)$ is the free chloride ion concentration at depth x and time t (%), $C_s$is the surface chloride concentration, determined by fitting with Origin (%), D_a is the apparent chloride, m^2/s, and erf denotes the statistical error function.

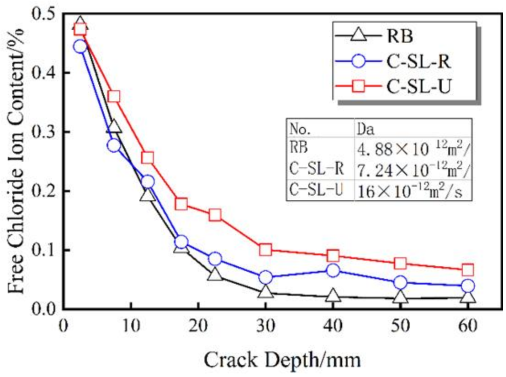

Fig. 7: Free chloride ion concentration profiles at different depths under sustained loading
Source: created by the authors.

Figure 7 plots the curve of distribution of free Cl-ion content at different depths of different cross-sections, and fits the distribution curves of Cl-ion diffusion coefficient. Within 30 mm depth, the difference in the free chloride ion content of repaired and unrepaired beams is about 0.1%, reflecting the notable repair effect. Beyond 30 mm depth, the effect becomes smaller, as the chloride ion content gets closer to that of the unrepaired crack. Overall, the D_a value of the repaired concrete parts reduced by about 54.75% relative to the unrepaired parts, but was still larger than that of the intact parts.

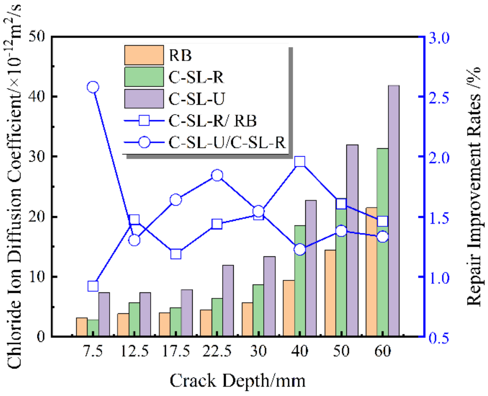

Fig. 8: Comparison of chloride diffusion coefficients (D_a)and repair improvement rates across different depths
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For a clearer presentation of repair effects at different depths, Equation (4) is obtained by inverting Equation (3):

$$D(x) = \frac{1}{4t}\left(\frac{x}{\mathrm{erf}^{-1}\left(\frac{C_s - C(x)}{C_s}\right)}\right)^2 \quad (4)$$

To calculate chloride diffusion coefficients at different depths using the method above, we simplified the calculation as follows: The concentration of chloride in the first sampling segment (0–2. 5 mm) was assumed to be the surface chloride concentration. Cs; for all other segments, chloride concentration was taken as the measured value at the midpoint of each segment. For the calculations, we use x to represent the depth, which is the vertical distance between the centre of the current segment and the centre of the first sampling segment (1.25 mm). When generating a data table that related depth to diffusion coefficient, again, the midpoint of each sampling segment was used as the representative depth, but diffusion coefficients Di fitted layer by layer are better able to characterise the distribution of properties and diffusion behaviour. When making the data table for depth to diffusion coefficient, we again use the middle of each of the sampling segments as the representative depth, and fit the diffusion coefficients Di layer-by-layer for a better portrayal of the distribution and diffusion behaviour. Although in Equation (3) the apparent diffusion coefficient is assumed to be a constant, a material property, to evaluate the macroscopic behaviour, in Equation (4) an inverse approach for its depth dependence is applied. Thus, D(x) here serves only as a computational variable to quantify "the remediation effect of MICP mineralisation along the crack depth" for the gradient. Calculating values for discrete depth intervals gives the spatial distribution of the repair efficacy, showing how the mineralised barrier effectively recompensates for the concrete heterogeneities caused by the curving fracture geometry.

Layer-by-layer fit was performed using the Curve Fitting Toolbox from MATLAB. The Fick's second law equations were solved using a non-linear least-squares method: Levenberg–Marquardt algorithm. To further confirm the true diffusion coefficients we have determined, we evaluated the goodness of fit for each fitting cycle, and all the fitted values gave a coefficient of determination $R^2 > 0.90$. This rigorous calculation provides a strong match between experimental chloride concentration profiles and the theoretical diffusion models.

Figure 8 illustrates the improvement effects. Figure 8 shows the depth profile of the chloride ion diffusion coefficient in the intact section, unrepaired section and diffusion method-repaired section. A transverse analysis of cracks (along the concrete depth direction) showed that all three beams' chloride ion diffusion coefficient increased with depth along the concrete depth, consistent with the retarding effect of conventional concrete on ion diffusion. At a shallow depth of 7.5 mm, the diffusion coefficient of the repaired beam was significantly lower than that of the unrepaired beam and approached that of the intact beam. This result is consistent with [14] and with previous reports that microorganisms situated close to the surface stimulated more intense CaCO3 precipitation. For the 7.5–30 mm range, there is a considerable improvement rate of the repaired beam; however, at a depth of 12.5 mm, the rate is about 130% instead, owing to uneven deposition, which brings down the repair effect in a short time. Beyond 30 mm, diffusion coefficients of the three groups began to converge, and the difference became gradually smaller. The repaired beam showed a certain degree of improvement, but this improvement was small, between 20% and 50%. These results suggest that in deeper regions, Ca^{2+} diffusion is confined, decreasing the repair rate and rendering the repair process more reliant on the pore structure of the concrete matrix. In summary, the diffusion method makes even more successful precipitation of calcium carbonate in shallow areas, in which oxygen content is relatively high and microbial activity is relatively strong, helpful in inhibiting chloride corrosion. However, in deeper regions, both a limited Ca^{2+} diffusion and an unfavourable reaction environment prevent the formation of a continuous dense minerals layer and poor remediation performance.

3.3 Comparison of Two Repair Methods

Both injection and diffusion methods were able to achieve crack sealing after the repair cycle and exhibit obvious and prominent repair effects. For the injection method, the continuous injection of the repair solution lasts for 17 days, then it stands in water for an immersion cure of 10 days, which will form a white deposited layer on the surface of the crack. Finally, mixing the diffusion method + injecting bacterial solution in gel solutions, for controlled release, fully sealed cracking by about the tenth day. Although the procedures are quite different, both methods did a good job of filling the cracks and improving the surface and durability of the concrete.

Due to the multiscale randomness in the cementitious matrix and the complicated geometry of the flexural crack, the chloride concentration distribution of flexurally cracked concrete has a strong stochastic nature. Diffusion-driven transport process is not linear but a ‘multiscale’ process, where local variations in pore structure and the mineralised MICP barrier greatly affect the macroscopic diffusion coefficient. Given this stochastic aspect, the actual 54.75% decrease in Da is understood as the formation of a relatively stable mineralised layer that greatly reduces the possible paths of chlorine ingress probabilistically even under wet–dry cyclic cycling.

For the macro-performance evaluation, both repair methods significantly enhanced the chloride ion corrosion resistance of the cracked region. After injection repair, the chloride ion migration coefficient was reduced from $15.3(\pm1.0)\times10^{-12}\,m^2/s$ to $6.5(\pm0.4)\times10^{-12}\,m^2/s$, decreasing by about 57.5%. Following the diffusion-based repair, the chloride ion diffusion coefficient at the cracked cross-section of the sustained loading beam is from $16\times10^{-12}\,\mathrm{m^2/s}$ down to $7.24\times10^{-12}\,\mathrm{m^2/s}$, that is to say, decreased by approximately 54.75%. The diffusion method greatly improved resistance to Cl penetration, with a little lower improvement for the injection method, because it was performed under long-term loading, whereas the injection was under unloaded conditions.

Furthermore, SEM and XRD characterisation also highlighted differences for each repair method in terms of different products generated and their impacts on the product properties. The repair sample treated with the injection method contained rhombohedral calcite, spherical vaterite, a few acicular crystals of calcium acetate and reasonably loose deposits; the remainder is local vacant space. Unlike the samples repaired by the diffusion method, the samples repaired by the diffusion method mainly featured vaterite crystals, which were packed and uniformly distributed in bulk. Such differences are mainly due to the different modes of ion supply and duration of exposure, [15]. The injection method quickly injects a large volume of the repair solution, making localized concentrated areas and consequently loose deposits. After a long curing period, the initially grown spherical-type vaterite gradually transforms into the more stable calcite phase. Meanwhile, the slow-release process of the diffusion method can induce steady diffusion of ions, which benefit development of uniform and compact mineral deposits; this phenomenon is consistent with the conclusions of [16] conclusions, which have demonstrated that a slow supply of carbonate ions favours the formation of structurally uniform calcium carbonate deposits. Consequently, in the presence of the pore solution, it first experiences a “dissolution–reprecipitation” process, to evolve into the more stable thermodynamically calcite phase. Summary of this kinetic transformation gives the initial repair layer a gradual transition to form a chemically stable, mechanically strong barrier—it further adds resistance to chloride ion penetration.

In conclusion, the injection method needs a longer repair time, and the last products are made of stable calcite. The diffusion method gives effective repairs in a shorter time, and the products are predominantly made up of metastable vaterite. But even in all-state loading conditions, it could afford the resistance to chloride ion transfer comparable to that of the injection method. And as the repair duration increases, its resistance to permeability will also improve, [17], [18]. Thus, this diffusion method can be both constructed simply and has strong long-term potential for engineering purposes.

3.4 Comparison of Multiple Repair Methods

As shown in Figure 9, for cracks with a width ranging from 0.05 mm to 1.0 mm, the injection method performed well [19], with the permeability coefficient being reduced by 2–4 orders of magnitude, and the electrical flux reduced by 25–70%, [20], [18], [21], [22]. Moreover, if the crack dimension is 2.0 mm, the water seepage rate reduces to only 12% of the original one, [23]. The immersion method was also remarkably efficient for 0.15 mm–1.64 mm cracks and lowered the permeability by 2–3 orders of magnitude, [23]. The spray method primarily improved the permeability of a completely solid surface of concrete, reducing its water absorption by about 60%. It was quite an effective treatment on the surface, but also had a limited effect on Cl diffusion suppression, [18]. The self-healing method is suitable for cracks smaller than 0.5 mm, providing a repair rate of waterproof cracks better than 80%, [20]. But residual life microbial reaction will change the pore structure, resulting in the Cl^- diffusion coefficient increase, [14]. The diffusion method is suitable for repairing concrete. After sealing cracks of 0.085 mm, the apparent chloride ion diffusion coefficient of concrete reduced by approximately 50%, which is close to the effect achieved with the injection method.

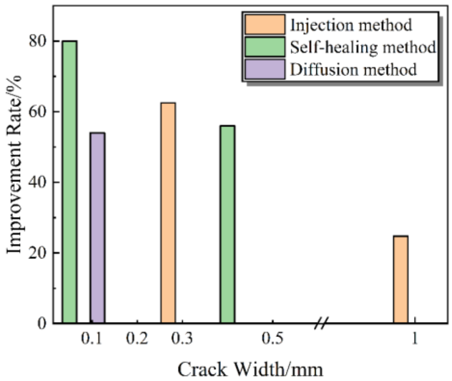

Fig. 9: Comparative repair efficacy of different methods based on crack width and improvement rate
Source: created by the authors.

4 Conclusions

(1) The diffusion method has good sealing ability for a shallow crack (0–30 mm), and the chloride diffusion coefficient decreases approximately 50%. Though the capability of repairing deeper cracks (>30 mm) is not so good, it still has a better repair effect on the unrepaired cracked zone overall. Shows that this diffusion method can greatly improve concrete's resistance to the chloride ion diffusion.

(2) Diffusion-repaired materials consist of spheres of vaterite crystals packed closely together. Gradually over time, the initially formed vaterite gradually transforms into calcite. Our result implies that the diffusion method has a 'stepwise deposition–crystal evolution' process of sedimentation.

(3) Our study has confirmed that the diffusion method can still restore cracks, under sustained loading, with effective chloride ion resistance similar to that of the unloaded specimen restored by the injection method, even though the latter also takes a considerably longer treatment period.

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APPENDIX

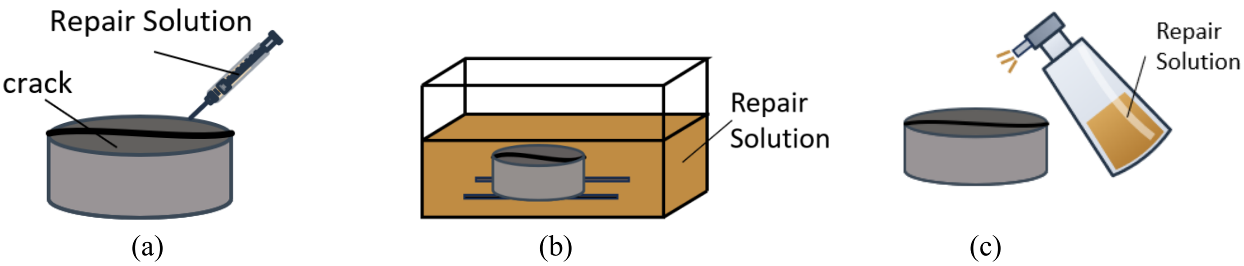


Fig. 1: Schematic diagram of the repair methods: (a) Injection; (b) Immersion; (c) Spraying

Source: created by the authors.

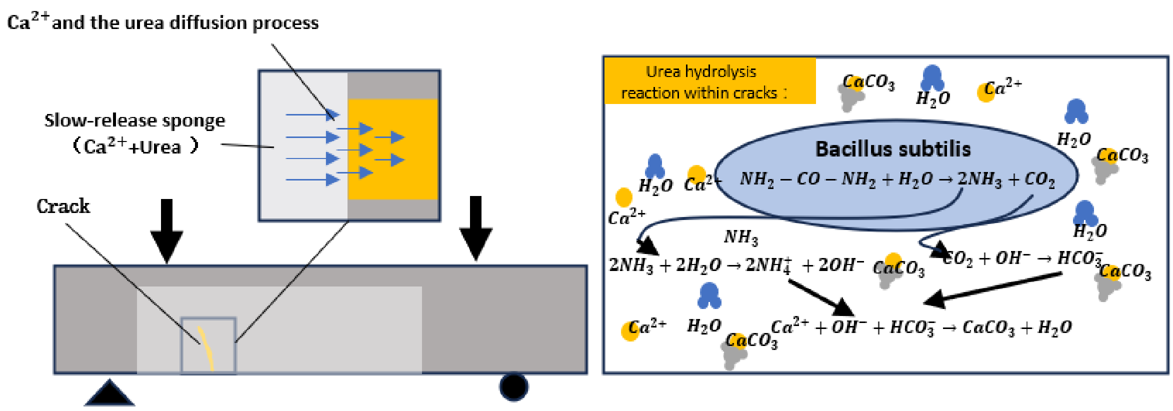


Fig. 2: Schematic representation of the diffusion-based repair mechanism

Source: created by the authors.

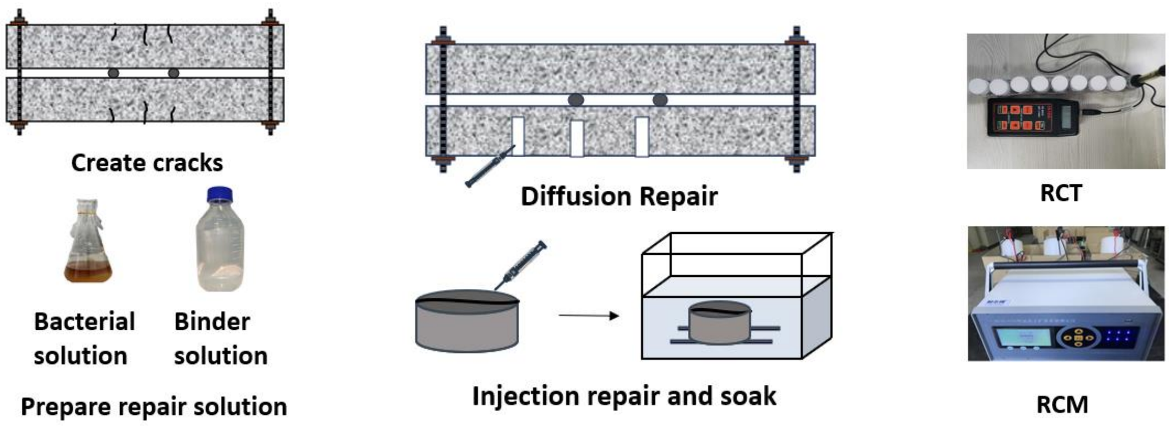
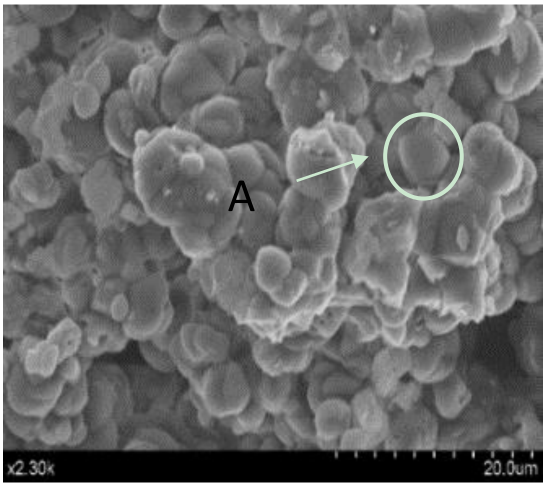
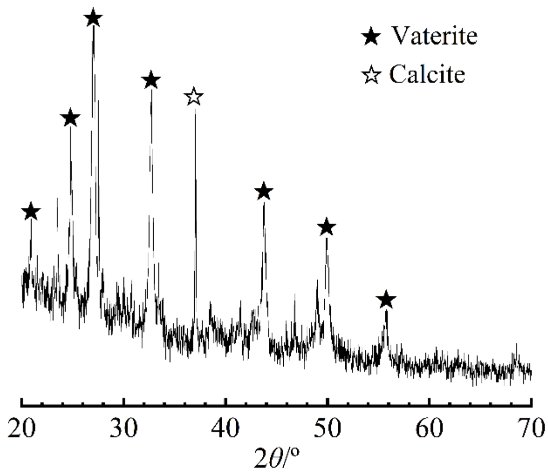


Fig. 3: Experimental workflow: (a) Preparation; (b) Repair process; (c) Testing phase

Source: created by the authors.



(a)



(b)

Fig. 6: Microstructural characterisation of diffusion-repaired products: (a) SEM morphology; (b) XRD pattern

Source: created by the authors.

Table 1. Details of test specimens

Operating conditions	Number	Crack width /mm	Crack Repair Methods	Post-production test specimen type
Unload	RB	——	——	Beam
Unload	C-UL-U	0.081	——	Cylindrical specimen
	C-UL-R	0.086	Injection method (17 d) + Soak (10 d)	Cylindrical specimen
Sustained Loading	C-SL-U	0.076	——	Beam
	C-SL-R	0.085	Diffusion Method (10 d)	Beam

Source: created by the authors.

Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

The authors equally contributed in the present research, at all stages from the formulation of the problem to the final findings and solution.

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Conflict of Interest

The authors have no conflicts of interest to declare that are relevant to the content of this article.