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Durability assessment of repairing vertical cracks in concrete using microbially induced calcium carbonate precipitation technique

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ABSTRACT

In order to explore the effectiveness of microbially induced carbonate precipitation (MICP) technique in repairing concrete cracks, several concrete cylinder specimens with vertical crack widths of 0.1 mm, 0.2 mm and 0.4 mm were repaired by MICP technique with diffusion method and injection method. Their effectiveness of crack repair in concrete was assessed by durability improvement in permeability and chloride resistance and microstructure analysis. The results show that the sponge strip used in diffusion method not only store cementation solution, but also provide attachment point for calcium carbonate deposition. The waterproof performance and chloride resistance of concrete specimens with three crack widths repaired by diffusion method were better than those treated by injection method. The average improvement coefficients of permeability and chloride resistance reach 79.7% and 60.9%, respectively. The research achievements indicate that the MICP technique with diffusion method is an effective way to repair the vertical cracks on the surface of structural concrete, which can provide some reference for practical engineering in concrete crack repair.

1. INTRODUCTION

Concrete structures have been widely used in civil engineering. However, due to the low tensile strength of concrete, cracks inevitably appear in concrete members under the action of load and other factors. In coastal areas, some aggressive media such as chloride ions will penetrate into concrete through cracks more quickly. As a result, the corrosion of steel bars is aggravated and the safety and durability of concrete structures will be affected (Lu et al., 2014; Fan et al., 2021). Therefore, it is necessary to repair the surface cracks in existing concrete structures quickly and effectively.

In the field of civil engineering, microbially induced carbonate precipitation (MICP) technology was first applied to sandy soil reinforcement and cultural relics protection (Dejong et al., 2006; Tan, 2017). After that, this technology is used in concrete crack repair. Choi et al. (2017) repaired mortar samples with crack width of 0.15~1.64 mm by MICP technology. The test samples were immersed for 21 cycles and their permeability coefficient decreased by about three orders of magnitude. Tittelboom et al. (2009) used the method of injection and immersion to repair concrete samples with crack width of 0.1 mm by MICP for 3 days. The results showed that the effectiveness of MICP technology was similar to that of epoxy resin and superior to that of cement mortar. Lian et al. (2019) repaired the concrete samples with different crack widths (0.3 mm、0.5 mm、1.0 mm、1.5 mm and 2.0 mm) by MICP technology. The permeability coefficient of test samples repaired by injection and grouting method was decreased from 10^{-4} m/s to 10^{-8} m/s. Yuan et al. (2020) repaired concrete samples with crack width of 1 mm by MICP technology. The electric flux of the samples repaired by injection for 12 times decreased by about 25%, and the frost resistance and sulfate aggression resistance of these samples were improved. In summary, the impermeability, frost resistance and sulfate aggression resistance of concrete will be improved by MICP technology.

For above mentioned researches, the cracks on the horizontal plane were usually adopted in their studies. The repair solution can easily penetrate into the cracks under the action of gravity. However, it is difficult for the repair solution to retain in vertical cracks. Therefore, the selection of repair methods for vertical cracks is required for civil engineers. Based on the above problems, the diffusion method for MICP technology was proposed in this paper. This method was adopted to repair the vertical cracks in concrete (the crack width is 0.1 mm、0.2 mm and 0.4 mm) by microbial mineralization. Meanwhile, the injection method was adopted for comparison. The composition and micro-morphology of the materials in the cracks of the specimens before and after repair were observed. The waterproof performance and resistance to chloride aggression of the test specimens were investigated. Finally, the effectiveness of diffusion method was evaluated, and the feasibility of this method was verified.

2. EXPERIMENTAL INVESTIGATIONS

2.1 Concrete specimens

The concrete samples were made by P.O 42.5 ordinary Portland cement, natural river sands with fineness modulus of 2.7 and gravels with particle size of 5~31.5 mm. The mixing ratio of concrete is shown in Table 1. The compressive strength of cubic concrete specimen (150 mm × 150 mm × 150 mm) after standard curing for 28 days was 32.2 MPa.

Table 1. Mixture ratio of concrete (kg/m^3)

Cement	Water	Sand	Gravel
449	220	615	1116

Cylindrical concrete specimens (Φ100 mm×50 mm) were used for microbial mineralization remediation. According to the relevant regulations on the maximum crack width of concrete members in codes (ACI 318, BS 8110 and GB 50010-2010), three crack widths of 0.1 mm, 0.2 mm and 0.4 mm were prepared in this test. In order to obtain ideal crack parameters (length, depth and width), prefabricated cracks in concrete samples were formed by steel plate insertion and removal method. Before concrete samples were made, lubricating oil was brushed on the surface of steel sheet to prevent adhesion between steel plate and concrete. The steel plates were slowly pulled out from the hardening concrete after about 16~18 hours of pouring. Finally, the cracked samples were cured in the standard curing box for 28 days (see Figure 1), and then used for crack repair test.

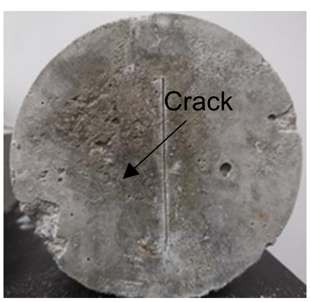

Figure 1. Concrete specimen with precast crack

2.2 Bacteria and cementation solution

In this study, ureolytic bacteria of Bacillus pasteurii (*Sporosarcina pasteurii DSM 33*) was adopted. The growth medium was composed of 20 g/L yeast extract, 15 g/L NH_4Cl and 1 mol /L $NiCl_2$, with a pH value of 9.2~9.3. The medium was sterilized by high pressure steam for 3 hours. Bacteria were shaken at constant temperature (28℃, 180 r/min) for 48 h after inoculation. Finally, the urease activity measured by conductivity method was 20~28 U/ml.

Usually, $CaCl_2$ was adopted as calcium source in microbial mineralization research. However, corrosion of steel bars will be accelerated by chloride. It is unfavorable to the durability of reinforced concrete structures. Therefore, $Ca(CH_3COO)_2$ was selected as calcium source in this study. 1mol/L urea and 1 mol/L calcium acetate solution were prepared respectively. Then, the above two solutions were mixed. The mixture is the cementation solution.

Meanwhile, the influence of chloride ions in the culture medium on the results should be eliminated. The supernatant was removed by centrifugation before the bacterial solution was used. Subsequently, sodium acetate solution (10 g/L) was added to the substrate. The above operation was repeated once. The solution obtained by the above operation was bacterial solution.

2.3 Crack repair methods

Before repairing, the crack on one side of the cylinder samples were stuck with foam tape in order to prevent the loss of repair solution from this side. Next, the crack on the other side of the sample were repaired. In view of the vertical cracks on the surface of samples, the diffusion method for MICP technology was proposed here. At the same time, the injection method as a comparison was also adopted. The steps of the above two methods are described as follows.

(1) Diffusion method. The bacterial solution was slowly injected into the crack. Then, about 3 ml of cementation solution was injected into the sponge strip. At this time, the sponge strips are saturated and the cementation solution will not drip from the sponge. It can prevent the bacterial solution which has been injected into the cracks from penetrating into the sponge. Finally, the sponge strips with cementation solution were fixed at the cracks with transparent tapes. Thereafter, the above operations were repeated once a day for 16 days. The diffusion method is shown in Figure 2.

(2) Injection method. The bacterial solution and cementation solution were mixed at a ratio of 1:1, and then the mixed solution was filled with cracks by injectors. The mixture was injected once a day for 16 days. The injection method is shown in Figure 3.

Figure 2. Diffusion method

Figure 3. Injection method

2.4 Evaluation of repair effectiveness

(1) Microscopic analysis
The composition of the materials inside the cracks was determined by X-ray diffraction (XRD). Meanwhile, the morphology of the materials in cracks was analyzed by scanning electron microscope (SEM).
(2) Macro performance test
Referring to the method of capillary water absorption test in the previous study (Xu and Wang, 2018), the waterproof performance of the samples was tested. The chloride aggression resistance test was also carried out according to the electric flux method recommended by GB/T 50082-2009. The waterproof performance improvement coefficient λ_W and the chloride aggression resistance improvement coefficient λ_{Cl} were proposed to evaluate the repair effectiveness. The improvement coefficient λ can be uniformly calculated by the following formula:

$$\lambda=\left|\frac{P_r\text{-}P_u}{P_l\text{-}P_u}\right|\times 100\% \quad (1)$$

where, P_l, P_r and P_u represent the performance parameters of intact specimen, repaired cracked specimen and unrepaired cracked specimen, respectively.

3. RESULTS AND DISCUSSION

3.1 Surface observation of cracks

With the progress of crack repair, white precipitates were continuously formed and accumulated in cracks. Finally, the cracks were completely blocked by these white precipitates. The crack surface condition of specimens with crack width of 0.2 mm repaired by diffusion method is shown in Figure 4. It can be seen that the white precipitates were gradually deposited from the lower part of the crack to the upper part during the repair process. This phenomenon is attributed to the influence of gravity. Under the action of gravity, calcium carbonate was first deposited in the lower part of the crack.

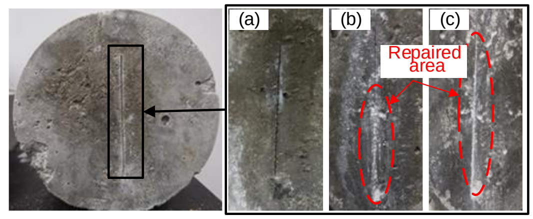

Figure 4. Surface condition of specimen with initial crack width of 0.2 mm repaired by diffusion method: (a) Before repair; (b) Under repair; (c) After restoration

3.2 Microscopic analysis

The composition of the product is mainly related to calcium source. In this test, the calcium source used in injection method was same as that used in diffusion method. Therefore, only the product components of diffusion method were analyzed. For the specimens with the initial crack width of 0.1 mm, the XRD patterns of the materials in the cracks of the unrepaired and diffused specimens are shown in Figure 5. The internal crystal morphology of cracks of unrepaired specimens, specimens repaired by diffusion method and specimens repaired by injection method are respectively shown in Figure 6.

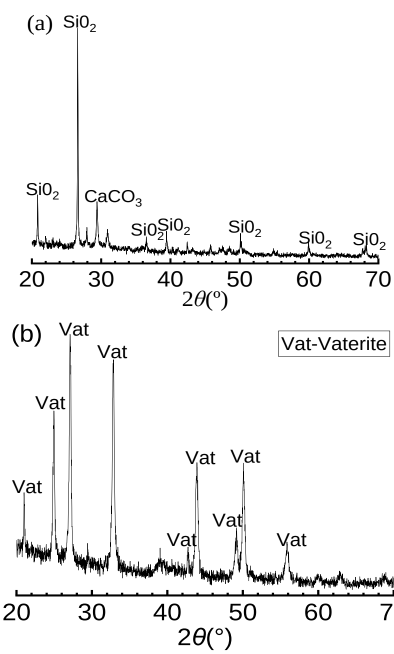

Figure 5. The XRD pattern of the material in the crack of the specimen with the initial crack width of 0.1 mm: (a) Unrepaired; (b) Repaired by diffusion method

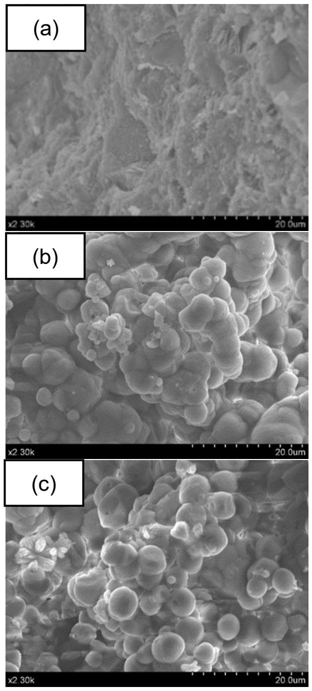

Figure 6. Morphology of material in cracks of specimen with initial crack width of 0.1 mm: (a) Unrepaired; (b) Repaired by diffusion method; (c) Repaired by injection method

It can be concluded from Figure 5 that the materials in the cracks of unrepaired specimens were common components of cement-based materials (silica and a small amount of calcium carbonate, etc.) (Zhang et al., 2013), while the generated materials in cracks of specimens repaired by diffusion method were vaterite. This finding proves that the crack repair using MICP technique is the result of calcium carbonate deposition in cracks.

As shown in Figure 6, spherical calcium carbonate deposited by diffusion method (Figure 6b) was stacked into clusters. This might be attributed to the fact that sponge strips in diffusion method can not only provide cementation solution, but also provide attachment points for products. Therefore, calcium carbonate is allowed to cross-link and grow at the crack inner wall and crack opening (Wang et al., 2008).

3.3 Waterproof performance

The cumulative capillary water absorption height i (mm) of the samples was calculated according to the formula (2) (Liu et al,. 2018).

$$i = \frac{m_s - m_d}{A\rho_w} \quad (2)$$

where, m_s is the mass of the specimen after absorbing water (g); m_d is the mass of dry specimen (g); A is the area of contact surface between specimen and water (mm^2); ρ_w is the density of water, (g/mm^3)

When the cumulative capillary water absorption height was taken as a calculation parameter, the waterproof performance improvement coefficient λ_w can be determined by Eq. (1) and their corresponding results are shown in Figure 7. It can be observed from Figure 7 that the λ_w value of the samples repaired by diffusion method was higher than that of samples repaired by injection method. This phenomenon may be attributed to the fact that the sponge in the diffusion method can provide attachment points for product deposition. More calcium carbonate precipitates were generated at the crack openings. Therefore, the waterproof performance of the samples repaired by the diffusion method is better. For the same repair method, λ_w decreases with the increase of crack width. After repaired by diffusion method, the λ_w values of specimens with crack widths of 0.1 mm, 0.2 mm and 0.4 mm were 84.2%, 81.2% and 73.6% respectively. The reason for this phenomenon is ascribed to the fact that calcium carbonate particles are easier to adhere to the inner wall of cracks with smaller width, which is more conducive to the accumulation of products (He et al., 2019).

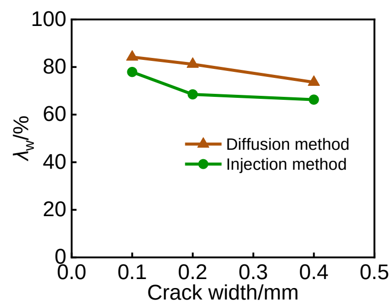

Figure 7. The improvement coefficient of the waterproof performance of all specimens

3.4 Resistance to chloride aggression

Figure 8 shows the results of electric flux of all test samples. It can be observed from Figure 8 that for the samples with the same crack width, the electric flux of the specimens repaired by diffusion method is lower than that of the specimens repaired by injection method. According to the result of electric flux, the λ_{Cl} of each specimen was calculated by Eq. (1) and the result is shown in Figure 9.

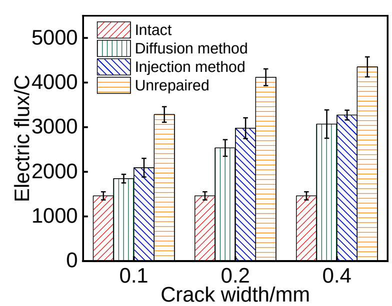

Figure 8. Electric flux of test specimens within 6h

As observed from Figure 9, the resistance to chloride aggression of the specimens repaired by diffusion method was significantly improved, which indicates the improvement effectiveness of diffusion method is better than that of injection method. Combined with the SEM image in Figure 6, it is believed that the cracks in the specimen repaired by diffusion method are filled more densely. This shows that calcium carbonate precipitations deposited in cracks can not only block water transmission, but also weaken chloride aggression. When the crack width increases from 0.1 mm to 0.4 mm, the λ_{Cl} of the specimens repaired by diffusion method decreases from 78.78% to 44.33%. It means that the repair effectiveness gradually decreases with the increase of crack width.

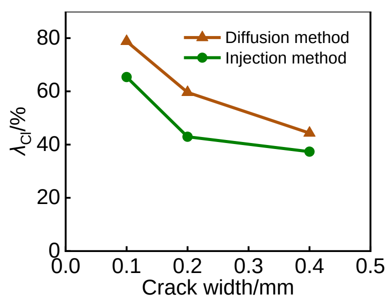

Figure 9. The improvement coefficient of chloride aggressive resistance of all specimens

4. CONCLUSIONS

$CaCO_3$ crystals were cross-link and clustered in cracks of specimens repaired by diffusion method. Cracks were blocked by calcium carbonate. Therefore, the waterproof performance and chloride aggression resistance of the specimens were improved. For samples with small crack width, calcium carbonate is easier to adhere to the inner wall of cracks. Therefore, diffusion method is more effective for samples with smaller crack width.

The waterproof performance and chloride aggression resistance of the samples repaired by diffusion method were higher than those of injection method. For cracked specimens with three crack widths, the average improvement coefficients of waterproof performance and chloride aggression resistance repaired by diffusion method reached 79.7% and 60.9%, respectively. It can be concluded that diffusion method is more suitable for repairing vertical cracks than injection method.

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