*Int. J. Electrochem. Sci.*, 16 **(2021)** Article Number: 211217, doi: 10.20964/2021.12.19

**International Journal of**
**ELECTROCHEMICAL**
**SCIENCE**
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# Investigation of concrete crack repair by electrochemical deposition

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*Received:* 24 August 2021 / *Accepted:* 23 September 2021 / *Published:* 10 November 2021

Cracks in reinforced concrete structures are inevitable in the process of use. Cracks not only affect the aesthetics of the structure appearance, but also affect the overall performance of the structure and shorten its life. Traditional methods are limited for repairing cracks in reinforced concrete in an aqueous environment. Electrochemical deposition is a relatively new method for repairing cracks in reinforced concrete, which fills and heals cracks in concrete, and increases the alkalinity of the surroundings of the reinforcing steel in concrete, slowing down the reinforcing steel corrosion caused by harmful substances. In this study, the changes in the surface coverage of the concrete specimens during the repair process were studied. Three different concentrations of electrolyte solutions were tested with three different intensities of electric current. The test results showed that the surface coverage of the concrete specimens was increasing during the repair process. The repair depths of the cracks on the specimens were measured by three different intensities of electric current to three different concentrations of electrolyte solutions at different times. The results showed that the repair rate of the crack depth of the specimens increased and then decreased with the increase of the current intensity. It can be concluded that the rate of crack repair increases with the current intensity and then decreases with the increase of electrolyte solution concentration.

**Keywords:** Crack repair; Electrochemical Deposition; Concrete; Mass change; Surface coverage

## 1. INTRODUCTION

Reinforced concrete is an important load-bearing element in architectures. In practice, cracks in reinforced concrete structures commonly occurred in the course of use. Multiple factors that can cause cracks in concrete structures include material quality, poor construction or maintenance conditions, temperature-induced thermal expansion and contraction, and uneven settlement of the foundation [1–3], which inevitably lead to cracks in the reinforced concrete structure in the process of use. After the cracks occur, external harmful substances will constantly penetrate into the concrete through the cracks and further aggravate the corrosion of the reinforced concrete [4–7]. Therefore, it is necessary to take measures to control the occurrence and development of cracks. Different methods can be applied in the repairing of cracks with different degree. Structural strengthening, surface treatment, grouting and filling methods are commonly used for repairing cracks in general onshore reinforced concrete structures [8–11]. However, most of these repair methods have limitations in the repair of cracks in reinforced concrete structures in water environments. Therefore, it is urgent to seek for a suitable method to repair cracks in reinforced concrete under water [12,13]. The electrochemical deposition method opens a new way to solve the problem by introducing electrochemical mechanisms and scientific crossover to transform unfavorable factors into applicable conditions [14].

Compared with the traditional repair methods, electrochemical rehabilitation techniques can eliminate the need to remove heavily carbonated or chloride-contaminated concrete retaining layers, which can save a lot of time and prevent the damage to the internal reinforcement of reinforced concrete caused by carbonation and chlorine contamination [15–17]. The electrochemical method can be adopted to repair cracks and surfaces in reinforced concrete by simply supplying an inert anode to the concrete in an aqueous environment and passing a certain amount of current between the reinforcement exposed on the outside of the concrete and the inert anode [18,19]. The application of electrochemical deposition method can greatly reduce the cost of repairing structural cracks in hydropower projects and marine projects, and effectively solve the technical problems of repairing concrete cracks in the water environment [20–23].

Since the late 1980s, Japanese scholars have been conducting research on the repair of cracks in reinforced concrete by electrochemical deposition [24,25], using cracked reinforced concrete in seawater as the target of the study. The steel reinforcement was used as the cathode and an inert anode was placed in the seawater with a certain intensity of current passing between them. The large amount of $Ca^{2+}$ and $Mg^{2+}$ ions in the seawater move towards the cathode by the effect of the potential difference and react with the $OH^-$ produced at the cathode to produce deposits that grow in the cracks of the sea concrete, thus healing the cracks of the reinforced concrete. These deposits not only provide a physical protection layer for the marine concrete, but also effectively prevent harmful substances from attacking the concrete. Ryu and Otsuki [26–28] were the first to conduct electrochemical deposition tests with dry shrinkage concrete specimens. The results of their tests showed that the electrochemical deposition products could fill the cracks and form a thin film on the surface of the concrete, and that the repaired specimens had better water resistance and could prevent the intrusion of harmful substances. They adopted permeability coefficient, pore distribution, mass change, ultrasonic wave velocity, bending strength, fracture closure length, and SEM to evaluate the effectiveness of the restoration. The results proved that the repair of the real structure by electrochemical deposition method is effective and feasible. The choice of electrolyte solution concentration has not been consistently recognized in the existing literature. However, it is generally accepted that the depth of fracture filling increases with the concentration of electrolyte solution, while the surface coverage and fracture healing rate decreases gradually. Yodudiati et al. [29] presented that the electrolyte solution concentration was most effective at 0.1 M. Jiang et al. [30] investigated the effect of concrete parameters on the deposition effect of the electrochemical deposition method in the process of repairing reinforced concrete, pointing out that the concrete mass increase rate increases gradually with the concrete water-cement ratio. Meanwhile, the fracture closure rate also increases, while the surface coverage rate is negatively correlated with the increase of the water-cement ratio. As the thickness of the concrete protection layer decreases, the concrete mass increase rate, crack closure rate and surface coverage rate increase gradually. As the width of concrete cracks decreases, the crack closure rate and surface coverage rate gradually increase.

Despite that some theoretical results have been obtained from these works, empirical formulae for quantitative prediction of the effectiveness of electrochemical deposition method for repairing concrete cracks have not yet been developed. The distribution of the electric field in the electrolyte solution and the motion pattern of ions in the electric field have not been systematically investigated. In this work, the proportion of C30 concrete was designed according to the actual requirements of the proportioning ratio. A large number of test specimens of reinforced concrete with pre-cracked joints were made. Currents with three different intensities (10 mA, 20 mA, 30 mA) and magnesium nitrate solutions with three different concentrations (for electrochemical tests) were set. The total mass, surface coverage, and depth of crack repair of reinforced concrete specimens were measured and recorded, and compressive strength tests were performed on specimens with different crack repair rates.

## 2. EXPERIMENTAL

### *2.1. Preparation of test specimens*

The equipment for making the test specimens included shovels, masonry tools, concrete mixers, iron plates, a mould of 70 mm × 70 mm × 210 mm, 8Φ bars (C: 0.30%, Mn:1.50%, P: 0.05%, S: 0.05%, Si: 0.60%) with 50 mm 90° bent at the front end of 250 mm long, clips of equal width to the mould and vibrating tables.

A 70 mm × 70 mm × 210 mm mold was adopted to produce small-size reinforced concrete test specimens to investigate the effectiveness of the electrochemical deposition method for repairing cracks in reinforced concrete.

Before making the test specimens, the mix ratio was determined through four design stages: preliminary calculation of the mix ratio, baseline mix ratio, laboratory mix ratio, and construction mix ratio. The materials were weighed and mixed according to the determined proportions. After the concrete was well mixed, the collapse degree was measured and the cohesiveness and water retention were checked. The final ratio of cement: sand: stone: water = 1.00:1.51:2.47:0.48. The amount of each component was calculated based on the obtained data of ratio. The components are weighed and poured sequentially into the concrete mixer for approximately 30 to 40 s. The concrete should be mixed several times with clean and moist masonry tools and shovels until it is homogeneous. The first half of the volume of concrete was injected into the mold, and the reinforcement was placed in the middle of the mold in the horizontal direction. The mold with reinforced concrete is placed on a vibration table and vibrated for about 20-30s until the surface of the concrete became slurry. The prepared concrete specimens were left to stand in a standard environment for 24h and the mold were removed. The remaining parts of the surface of the formed concrete specimen were smoothed. The molded and demolded specimens were maintained for 28 days at a constant temperature of 20 ± 3 °C in a standard environment with a relative humidity of 90%.

### 2.2. Electrochemical deposition

The test specimens of reinforced concrete were divided into 9 groups with 10 specimens in each group. For each test, one concrete test specimen was taken from each group and placed in nine buckets to perform electrochemical deposition tests under different variables. The titanium plate was placed in a container as the anode. The titanium plate in the solution and the reinforcement exposed on the outside of the concrete were connected to the positive and negative electrodes of the direct current source to form a closed circuit. The concentrations of $Mg(NO_3)_2$ electrolyte solutions were 0.1 M, 0.25 M and 0.5 M. A 0-30 V adjustable voltage regulator was adopted as an external power source and three different intensities of currents, which are 10 mA, 20 mA and 30 mA, were introduced into the capacitor. A separate experimental setup was built and three different concentrations of electrolyte solutions were added to the device with no current flow as a blank control group. Figure 1 shows the schematic diagram of the device for electrochemical deposition.

The electrolyte solution was changed once a week to maintain the concentration of the solution constant. The test environment was kept consistent during the test period. The extent of repair of reinforced concrete test specimens was measured and recorded every week. The rate of repair of crack depth, surface coverage and quality changes during the concrete repair process were recorded. After 4 weeks, the repair status of the test specimens were summarized and analyzed.

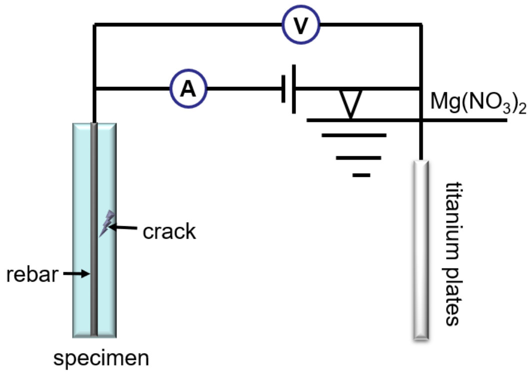

**Figure 1.** Schematic diagram of concrete crack repair by electrochemical deposition.

## 3. RESULTS AND DISCUSSION

Magnesium nitrate was used as electrolyte in this study, for the reason that it can produce deposits of magnesium hydroxide during the repair process. The mixed precipitate of magnesium hydroxide and calcium silicate becomes the main material for concrete crack repair. The electrochemical reaction at concrete is as follows:

Anode (titanium plate): $2H_2O + 2e^- \rightarrow O_2\uparrow + H^+$

Cathode (inside of concrete): $H_2O + 2\ e^- \rightarrow 2OH^- + H_2\uparrow$

Electrolyte (crack and surface): $Mg^{2+} + 2OH^- \rightarrow Mg(OH)_2\downarrow$

Since silicate cement was used in this test, a large amount of calcium silicate was presented in the cement, which led to the existence of the $Ca^{2+}$ ions. The sand used in the concrete test specimen contained a large amount of carbonate and silicate, which led to the existence of a great amount of $CO_3^{2-}$ and $SiO_3^{2-}$ ions. Therefore, the chemical precipitation process involves the following reactions:

$Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3\downarrow$

$Ca^{2+} + SiO_3^{2-} \rightarrow CaSiCO_3\downarrow$

The qualitative changes of the concrete specimens at various time periods in the electrochemical tests are shown in Table 1.

**Table 1.** Changes in test specimen quality.

| Concentration (M) | Current (mA) | Initial (g) | Week 1 (g) | Week 2(g) | Week 3 (g) | Week 4 (g) |
|---|---|---|---|---|---|---|
| 0.10 | 10 | 2900 | 2892 | 2877 | 2871 | 2865 |
| | 20 | 2889 | 2881 | 2878 | 2871 | 2866 |
| | 30 | 2940 | 2933 | 2931 | 2930 | 2929 |
| 0.25 | 10 | 2900 | 2887 | 2869 | 2851 | 2843 |
| | 20 | 2915 | 2910 | 2900 | 2884 | 2871 |
| | 30 | 2895 | 2866 | 2851 | 2840 | 2827 |
| 0.50 | 10 | 2897 | 2887 | 2879 | 2871 | 2857 |
| | 20 | 2903 | 2892 | 2877 | 2863 | 2849 |
| | 30 | 2910 | 2900 | 2887 | 2881 | 2877 |

As can be seen in Table 1, the quality of the reinforcement concrete specimens immersed in the $Mg(NO_3)_2$ solution tended to decrease to varying degrees at each time period during the electrochemical modification process. The free ions in the reinforced concrete specimens moved in the electrolyte, which causes the migration of various ions within the reinforced concrete. The amount of ion migration during this process is sufficient to bring about a mass reduction in gram level, which can be concluded from the presence of flocculent precipitation at the bottom of the barrel [31]. The data on the decreasing mass of the concrete specimen during the electrochemical modification process and the flocculent deposits analyzed during the electrochemical modification process further indicate that the possible existence of other chemical reactions during the electrochemical reaction cannot be ignored [32]. The presence of these reactions can result in a greater amount of decrease in the mass of the specimen than that of an increase in the mass of the specimen [33]. Therefore, it is inaccurate to measure the mass of electrochemical precipitate formation by weighing the total mass of the test specimens.

The main ions presented in silicate cements are $Ca^{2+}$, $CO_3^{2-}$ and $SiO_3^{2-}$ . A small number of free ions in the interior of the cement were transported by the reinforcement towards the electrolyte by the potential difference and reacted with the ions in the electrolyte solution. Two insoluble precipitates,

$Ca(OH)_2$ and $Mg(OH)_2$, formed by electrochemical reactions near the cathode, were immediately absorbed into the cracks in the concrete to repair the cracks and formed a protective layer on the surface.

**Figure 2.** Repair of the surface of the concrete test specimens at different times.

It is not prudent to measure the effectiveness and speed of crack repair by simply comparing the masses of the test specimens before and after the reaction. However, in order to obtain an incremental increase in specimen quality in the test, all errors in the test must be strictly controlled [34]. It is also important to ensure that the test specimens are similar to each other, thus the error caused by the difference of test specimens in the electrodeposition test can be eliminated [35]. Therefore, the following improvements were made to the electrochemical repair tests of cracks: 1) the test specimens of reinforced concrete were strictly controlled to ensure that the size and distribution of the reinforcement inside the test specimens were consistent [36]; 2) the surface of the test specimens were smooth and the roughness was controlled; 3) the cracks were prefabricated at the same location in depth and width; 4) The test under each working condition should be carried out simultaneously with several groups of test specimens for repairing the test, and the deposits on the test specimens should be peeled off in stages for weighing [37–42].

The changes in the surface coverage of the reinforced concrete test specimens during the restoration process are shown in Table 2. The table shows that the surface coverage of the reinforced concrete test specimens gradually increases with the repair time during the repair process. In addition, the rate of deposit formation on the surface of the concrete varies with the concentration of the solution and the intensity of the current in the test environment [43]. Figures 3 show the changes in the surface coverage of the test specimens during the cycles of the three different concentrations of $Mg(NO_3)_2$ electrolyte solution with three different intensities of currents, respectively.

**Table 2.** Variation of surface coverage of test specimens.

| Concentration (M) | Current (mA) | Initial coverage | Week 1 coverage | Week 2 coverage | Week 3 coverage | Week 4 coverage |
|---|---|---|---|---|---|---|
| 0.10 | 10 | 0% | 20.4% | 25.5% | 31.2% | 34.3% |
| | 20 | 0% | 21.2% | 27.9% | 37.4% | 38.6% |
| | 30 | 0% | 28.5% | 38.5% | 42.1% | 45.3% |
| 0.25 | 10 | 0% | 23.1% | 37.2% | 41.2% | 42.3% |
| | 20 | 0% | 28.6% | 39.8% | 47.1% | 49.2% |
| | 30 | 0% | 32.0% | 47.6% | 52.8% | 54.4% |
| 0.50 | 10 | 0% | 27.6% | 42.5% | 48.3% | 51.1% |
| | 20 | 0% | 32.2% | 47.5% | 55.4% | 61.7% |
| | 30 | 0% | 36.8% | 52.7% | 61.1% | 70.2% |

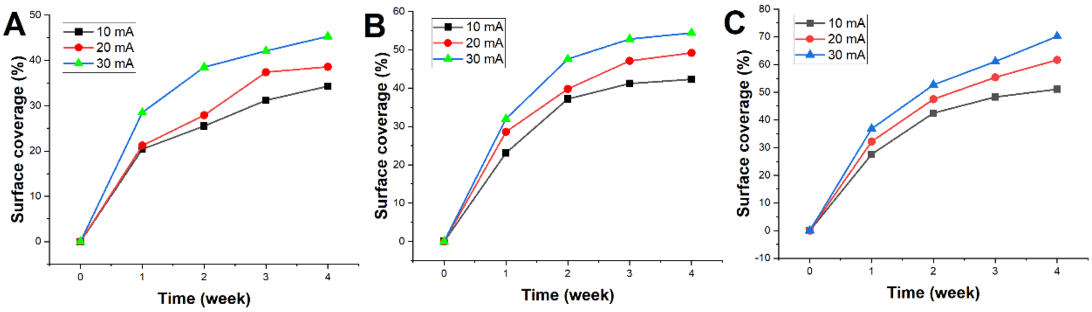

**Figure 3.** Surface coverage of the specimens at different currents in (A) 0.10 M, (B) 0.25 M and (C) 0.50 M of $Mg(NO_3)_2$.

The coverage of deposits on the surface of the specimen increases with the intensity of the applied current when reinforced concrete specimens in solutions of the same concentration are exposed to currents of different intensities. In the case that reinforced concrete specimens in different concentrations of solution are exposed to currents of the same intensity, the coverage of the surface of the specimens with deposits increases with the concentration of the electrolyte solution [44]. As the time increases, the increase of the deposit coverage tends to slow down significantly and level off gradually, which indicates that the electrochemical reaction is weakening as the contact area of the test specimen with the solution decreases [45]. Therefore, in the process of electrochemical repair of cracks in reinforced concrete, the current intensity and electrolyte concentration of the external power source have a positive correlation with the surface coverage of the specimens.

In practice, cracks in reinforced concrete can lead to a constant infiltration of harmful substances from the exterior of the concrete structure into the interior of the concrete through the cracks, which accelerates the corrosion of the concrete [46]. The main purpose of the electrochemical method of repairing reinforced concrete structures is to repair the structural cracks caused by various factors in the actual construction, thus the effectiveness of crack repair is the most important indicator of the electrochemical deposition method. The repair rates of crack depths in concrete specimens at various time periods in electrochemical tests are shown in Table 3.

**Table 3.** Repair rate of crack depth in reinforced concrete test specimens (%).

| Concentration | Current | 1 week | | | 2 Weeks | | | 3 Weeks | | | 4 Weeks | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Left | Middle | Right | Left | Middle | Right | Left | Middle | Right | Left | Middle | Right |
| 0.10 M | 10 mA | 0.0 | 0.0 | 0.0 | 2.1 | 0.2 | 2.6 | 5.2 | 2.5 | 5.3 | 5.7 | 2.1 | 5.3 |
| | 20 mA | 0.0 | 5.1 | 2.4 | 1.5 | 20.4 | 5.0 | 5.7 | 27.1 | 7.0 | 5.0 | 20.2 | 8.0 |
| | 30 mA | 0.0 | 7.4 | 3.0 | 2.0 | 30.3 | 10.2 | 7.6 | 33.5 | 8.0 | 10.5 | 45.5 | 10.6 |
| 0.25 M | 10 mA | 0.0 | 21.1 | 0.0 | 9.7 | 60.1 | 0.0 | 20.2 | 81.9 | 0.0 | 50.2 | 98.8 | 0.0 |
| | 20 mA | 0.0 | 20.2 | 0.0 | 3.6 | 53.5 | 6.7 | 11.3 | 75.5 | 21.1 | 21.1 | 65.1 | 30.2 |
| | 30 mA | 0.0 | 30.1 | 0.0 | 2.2 | 30.1 | 0.0 | 4.1 | 53.6 | 0.0 | 0.0 | 62.6 | 0.0 |
| 0.50 M | 10 mA | 0.0 | 21.2 | 0.0 | 6.2 | 42.1 | 13.3 | 8.8 | 70.3 | 22.5 | 45.7 | 100.0 | 62.5 |
| | 20 mA | 0.0 | 21.2 | 0.0 | 2.1 | 44.4 | 11.5 | 4.5 | 71.1 | 23.6 | 14.4 | 100.0 | 53.5 |
| | 30 mA | 0.0 | 27.6 | 0.0 | 7.9 | 41.5 | 5.6 | 8.8 | 73.5 | 7.8 | 10.6 | 100.0 | 19.2 |

As shown in Table 3, the lower the solution concentration and current intensity are, the less effective the repair of cracks in reinforced concrete is. The repair efficiency increases with the solution concentration and current intensity. However, it is not true that the higher the concentration of the solution and the current intensity are, the better the recovery results are [47]. Only with the appropriate concentration of solution and current intensity can the crack be repaired to the best effect. In addition, the depth of repair of cracks in reinforced concrete varies with the repair time to a certain extent.

The variation of crack depth recovery rate with current intensity in the electrochemical test is shown in Figure 4A. It can be seen from Figure 3A that, under the condition of constant concentration of electrolyte solution, the repair rate of concrete fracture depth shows a non-linear increasing trend with the current intensity, and the higher the current intensity is, the better the repairing effect is [48].

The variation of repair rate of crack depth with electrolyte solution concentration in the electrochemical test is shown in Figure 3B. As shown in Figure 4B, the depth recovery rate of concrete cracks increases with the electrolyte solution concentration at a constant energizing current intensity, but the correlation shows a non-linear behavior. From the analysis of the experimental data, it was found that both the current intensity and the concentration of electrolyte contribute to the depth of repair of concrete cracks by electrochemical deposition method in a certain range.

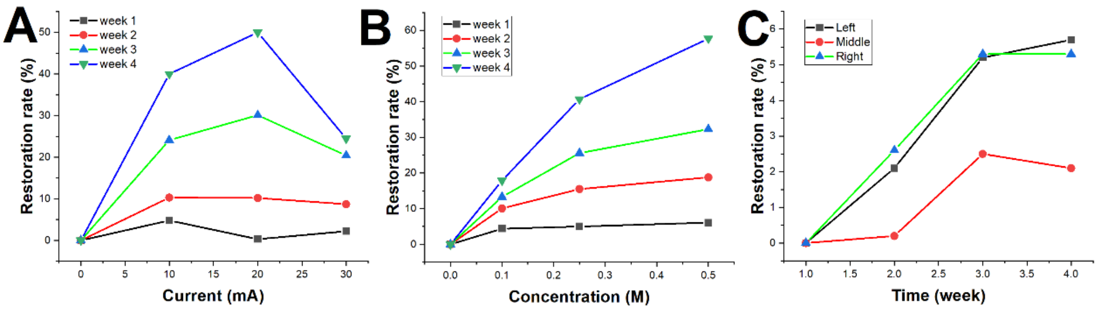

**Figure 4.** (A) Correlation curves of fracture depth repair rate with different current intensity along with the repair time. (B) Correlation curves of fracture depth repair rate with different concentrations of $Mg(NO_3)_2$ along with the repair time. (C) The trend of the depth repair rate of cracks at each location.

The main process of repairing cracks in reinforced concrete by electrochemical deposition can be summarized as follows: the deposition of the first week occurred mainly around the perimeter of the reinforcement, as the surface of the exposed reinforcement had the strongest electrochemical reaction and produced deposits at the fastest rate. With the continuation of the repair, deposits accumulated on the surface of the reinforcement and in the cracks. The electrochemical reaction was weakened and the rate of repair decreased. With the continuation of the repair, the condition of the repair was more satisfactory during the third week. Significant cohesive deposits were observed on the surface of the reinforced concrete, and large amounts of white precipitation were observed in the cracks. During the fourth week, the cracks close to the reinforcement were completely healed.

The main purpose of rehabilitating reinforced concrete is to restore and improve its mechanical properties. Therefore, it is necessary to test the mechanical properties of the rehabilitated reinforced concrete test specimens. The axial compressive strength was applied as the index of the mechanical performance test. At the end of the repair test with the electrodeposition method, axial compressive tests were performed on reinforced concrete specimens with different crack depth repair rates. This test can be applied in the examination of the effect of the crack depth repair rate on the axial compressive strength of the reinforced concrete specimens.

Table 4 shows the data of the mechanical performance tests. It can be noted from the table that the axial compressive strength of the reinforced concrete specimens gradually increases with the crack depth restoration rate. Thus the accumulation of deposits filling in the cracks restored the mechanical properties of the cracked reinforced concrete specimens. The axial compressive strength of the reinforced concrete specimens tends to increase linearly with the crack depth restoration rate, and the extent of increase is large, which indicates that the effect of the electrochemical deposition method on the improvement of the mechanical properties of reinforced concrete is highly significant.

**Table 4.** Data of the mechanical performance tests.

| Crack depth repair rate (%) | Load (KN) | Axial compressive strength (MPa) |
|---|---|---|
| 0 | 122 | 25.4 |
| 21.2 | 129 | 26.2 |
| 53.5 | 136 | 27.8 |
| 81.4 | 144 | 28.9 |
| 100.0 | 148 | 30.2 |

## 4. CONCLUSION

In this study, the concrete was designed and the final ratio was determined according to the actual ratio requirements. The concrete was mixed according to the final ratio and test specimens of reinforced concrete with pre-cracked joints were made. A subsequent investigation of electrochemical repair of cracks in reinforced concrete was carried out. Electrolyte solutions with three different concentrations and current with three different intensities were adopted to compare the repair results of the specimens. The mass change, surface coverage and depth of crack repair were monitored during the repair process. The mechanical properties of the specimens were also tested for different crack repair rates. Finally, the analysis of the test data was adopted to summarize the pattern of the repair effect of the test specimens over time.

ACKNOWLEDGEMENTS
This work was supported by Acoustic surface study for nonlinear multifield coupling (Chuzhou Vocational and Technical College, YJZ-2020-07), Study on application of solidification and stabilization technology of river sediment (Chuzhou Vocational and Technical College,YJZ-2019-13).

## References

1. Z. Cui, A. Alipour, *Constr. Build. Mater.*, 159 (2018) 652–671.
2. A. Bossio, F. Fabbrocino, T. Monetta, G.P. Lignola, A. Prota, G. Manfredi, F. Bellucci, *Corros. Rev.*, 37 (2019) 45–56.
3. A. Barrias, J.R. Casas, S. Villalba, *Sensors*, 18 (2018) 980.
4. L. Pahlavan, F. Zhang, G. Blacquière, Y. Yang, D. Hordijk, *Constr. Build. Mater.*, 167 (2018) 899–906.
5. Y.-S. Yang, C. Wu, T.T. Hsu, H.-C. Yang, H.-J. Lu, C.-C. Chang, *Autom. Constr.*, 91 (2018) 120–132.
6. M.R. Geiker, A. Michel, H. Stang, M.D. Lepech, *Cem. Concr. Res.*, 122 (2019) 189–195.
7. X. Xi, S. Yang, C.-Q. Li, M. Cai, X. Hu, Z.K. Shipton, *Eng. Fract. Mech.*, 199 (2018) 114–130.
8. M. Gkantou, M. Muradov, G.S. Kamaris, K. Hashim, W. Atherton, P. Kot, *Sensors*, 19 (2019) 5175.
9. L. Dai, H. Bian, L. Wang, M. Potier-Ferry, J. Zhang, *J. Struct. Eng.*, 146 (2020) 04020013.
10. Y. Ma, Z. Guo, L. Wang, J. Zhang, *J. Struct. Eng.*, 146 (2020) 04020117.
11. D.-C. Feng, X.-D. Ren, J. Li, *J. Struct. Eng.*, 144 (2018) 04018044.
12. A.I. Iakovenko, I.V. Kolchunov, *J. Appl. Eng. Sci.*, 15 (2017) 367–376.
13. X. Xi, S. Yang, *Constr. Build. Mater.*, 155 (2017) 114–125.

14. M.Á. Climent, M. Miró, J. Carbajo, P. Poveda, G. de Vera, J. Ramis, *Materials*, 12 (2019) 813.
15. J. Zhang, W. Jin, J. Mao, J. Long, X. Zhong, *Constr. Build. Mater.*, 237 (2020) 117629.
16. X. Kong, T. Tian, S. Xue, W. Hartley, L. Huang, C. Wu, C. Li, *Land Degrad. Dev.*, 29 (2018) 58–67.
17. J. XIA, S. JIN, X. HE, X. XU, W. JIN, *J. ZheJiang Univ. Eng. Sci.*, 53 (2019) 2298–2308.
18. W. Fan, J. Mao, W. Jin, J. Xia, J. Zhang, Q. Li, *Constr. Build. Mater.*, 251 (2020) 118872.
19. K. Zhang, J. Zhang, W. Jin, J. Mao, J. Long, *Constr. Build. Mater.*, 260 (2020) 120455.
20. J. Xia, X. Cheng, Q. Liu, H. Xie, X. Zhong, S. Jin, J. Mao, W. Jin, *Constr. Build. Mater.*, 250 (2020) 118898.
21. C. Pan, N. Chen, J. He, S. Liu, K. Chen, P. Wang, P. Xu, *Constr. Build. Mater.*, 260 (2020) 119724.
22. J. Mao, W. Jin, J. Zhang, J. Xia, W. Fan, Y. Xu, *Constr. Build. Mater.*, 213 (2019) 582–591.
23. L. Mao, Z. Hu, J. Xia, G. Feng, I. Azim, J. Yang, Q. Liu, *Compos. Struct.*, 207 (2019) 176–189.
24. J.-S. Ryu, *Mater. Struct.*, 34 (2001) 433–437.
25. N. Otsuki, M. Hisada, J.-S. Ryu, E. Banshoya, *Concr. Int.*, 21 (1999) 58–63.
26. J.-S. Ryu, N. Otsuki, *Cem. Concr. Res.*, 32 (2002) 159–164.
27. J. Ryou, P. Monteiro, *Can. J. Civ. Eng.*, 31 (2004) 776–781.
28. N. Otsuki, J.-S. Ryu, *J. Mater. Civ. Eng.*, 13 (2001) 136–142.
29. W. Yodsudjai, P. Suwanvittaya, *Asian J. Civ. Engeering*, 12 (2011) 197.
30. L. Jiang, H. Chu, *Adv Sci Technol Water Resour*, 25 (2005) 23–25.
31. J. Zhang, J. Mao, W. Jin, W. Fan, J. Xia, Y. Xu, Q. Li, *J. Cent. South Univ.*, 27 (2020) 2408–2423.
32. L. Teng, J. Weiliang, X. Chen, M. Jianghong, *J. Chin. Soc. Corros. Prot.*, 37 (2017) 382–388.
33. Y. Chen, W. Yao, J. Zuo, *Mater. Res. Express*, 5 (2018) 036508.
34. J. Hu, S. Li, Y. Lu, H. Zhang, M. Zhang, *Constr. Build. Mater.*, 249 (2020) 118717.
35. L. Landa-Ruiz, M.A. Baltazar-Zamora, J. Bosch, J. Ress, G. Santiago-Hurtado, V.M. Moreno-Landeros, S. Márquez-Montero, C.T. Méndez, A. Borunda, C.A. Juárez-Alvarado, J.M. Mendoza-Rangel, David.M. Bastidas, *Appl. Sci.*, 11 (2021).
36. J. Xu, F. Li, *Ocean Eng.*, 179 (2019) 38–50.
37. C. Pan, X. Li, J. Mao, *Materials*, 13 (2020) 1480.
38. J. Liu, T. Yang, J. Xu, Y. Sun, *Front. Chem.*, 9 (2021) 488.
39. S. Yan, Y. Yue, L. Zeng, L. Su, M. Hao, W. Zhang, X. Wang, *Front. Chem.*, 9 (2021) 220.
40. S. Wei, X. Chen, X. Zhang, L. Chen, *Front. Chem.*, 9 (2021) 697.
41. C. Li, F. Sun, *Front. Chem.*, 9 (2021) 409.
42. H. Karimi-Maleh, F. Karimi, L. Fu, A.L. Sanati, M. Alizadeh, C. Karaman, Y. Orooji, *J. Hazard. Mater.*, 423 (2022) 127058.
43. N.R. Yusupbekov, B. Eshmatova, U. Mukhamedkhanov, S. Gulyamov, *Int. J. Psychosoc. Rehabil.*, 24 (2020) 240–246.
44. J. He, X. Shi, *J. Mater. Civ. Eng.*, 32 (2020) 04020344.
45. J. Ramirez-Soto, J.T. Pérez-Quiroz, J.M. Salgado-López, M. Martinez-Madrid, T. Pérez-López, M. Rendón-Belmonte, E. Alvarez-Alfaro, *Rev. Alconpat*, 9 (2019) 167–184.
46. X. SONG, W. FAN, J. MAO, W. JIN, *J. ZheJiang Univ. Eng. Sci.*, 55 (2021) 511–518.
47. C. Pan, W. Jin, J. Mao, H. Zhang, L. Sun, D. Wei, *China Ocean Eng.*, 31 (2017) 631–638.
48. B. Chang, *Int. J. Nanotechnol.*, 17 (2020) 393–410.