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Innovative Electrochemical Deposition Techniques for Durable Concrete Crack Repair

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Author's contribution

The sole author designed, analysed, interpreted and prepared the manuscript.

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ABSTRACT

Electrochemical deposition repair (EDR) technology drives ionic species migration by applying an external electric field, generating insoluble crystalline precipitates within cracks to achieve autogenous healing and matrix reinforcement. This technology offers advantages such as superior micro-crack sealing capability, eco-friendliness, and enhanced durability. The EDR process includes electric field-induced ion transport, nucleation and crystal growth of deposition products, and crack infilling with interfacial bonding enhancement. Research shows that EDR technology can effectively seal crack apertures, reduce permeability coefficients, enhance flexural strength, and positively impact concrete chloride desalination and steel reinforcement repassivation. Factors influencing repair efficacy include electrolyte composition, current density distribution, and concrete matrix properties. Future research should integrate materials science, electrochemistry, and artificial intelligence to build a "mechanism-process-performance" integrated research framework, promoting the large-scale application of electrochemical deposition in engineering and supporting the green transformation of civil engineering materials.

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Keywords: Electrochemical deposition; concrete crack repair; ion migration.

1. INTRODUCTION

Concrete is one of the most widely used construction materials in modern civil engineering. However, due to its intrinsic brittleness and external environmental factors such as mechanical loading, thermal cycling, humidity fluctuations, and chemical attack, concrete structures inevitably develop micro- and macro-cracks during service. The presence of cracks not only affects the aesthetic integrity of concrete structures but also compromises their mechanical properties, accelerating the ingress of deleterious substances (e.g., chloride ions, oxygen, and moisture), leading to reinforcement corrosion and seriously threatening the structural durability and service safety of concrete structures. Therefore, timely and effective repair of concrete cracks is of significant engineering relevance (Guo, 2021). Traditional repair methods have certain limitations in repairing alkali-activated slag concrete (AASC) cracks, such as poor interfacial adhesion, low micro-crack repair efficiency, and limited penetration depth due to the porous microstructure and complex interfacial transition zones (ITZs) within concrete, resulting in suboptimal repair outcomes (Li & Xu, 2008; Yan et al., 2015; Wang et al., 2006; Qi et al., 2009; Li et al., 2024). Thus, researching innovative and practical methodologies for repairing concrete cracks is of great practical significance.

2. PRINCIPLES OF ELECTRODEPOSITION REPAIR OF CONCRETE CRACKS

Electrochemical deposition repair (EDR) technology drives ion migration in an electrolyte solution by applying an external electric field, generating insoluble precipitates (e.g.$Mg(OH)_2$、ZnO、$CaCO_3$），within cracks to achieve self-healing and matrix strengthening. This technology has demonstrated advantages such as strong micro-crack repair capability, environmental friendliness, and high durability in traditional concrete repair.

The typical process of electrodeposition repair of concrete cracks includes:

1. Electric field-driven ion migration: Using concrete as the cathode and an external electrode（e.g.,titanium mesh）as the anode, a direct or pulsed electric field is applied to drive ions such as Mg^{2+}、Zn^{2+}、Ca^{2+}、and OH^{2+}in the electrolyte toward the crack region.
2. Nucleation and growth of deposition reactions: The cathode surface undergoes a reduction reaction,$2H2O+2e^{-}\rightarrow 2OH^{-}+H_2\uparrow$，increasing local pH and promoting the combination of cations and anions to form precipitates such as Mg（$OH)_2$、ZnO or $CaCO_3$.

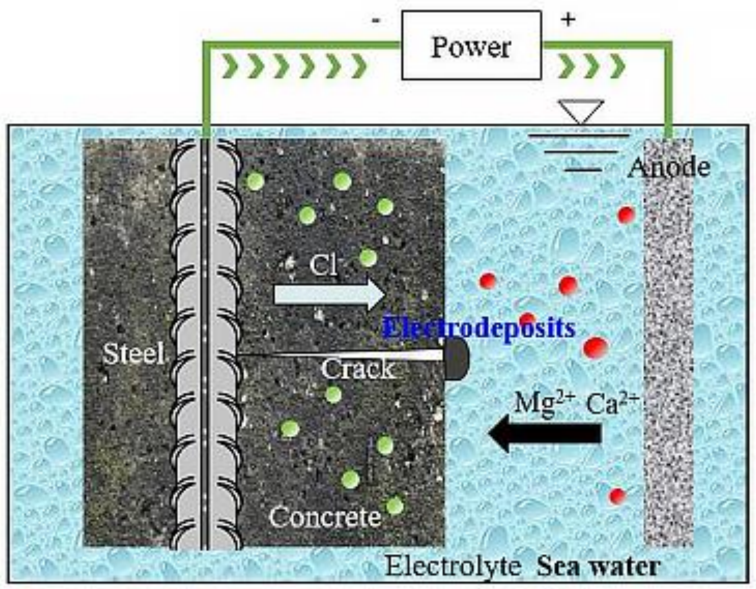

Fig. 1. Schematic diagram of the principle of electrodeposition repair of concrete cracks

3. Crack filling and interface strengthening: Deposits accumulate layer by layer within the crack, forming a dense protective layer that enhances interface bonding with the C-(A)-S-H gel of the concrete matrix through chemical bonding.

3. CHARACTERIZATION INDICATORS AND INFLUENCING FACTORS OF ELECTROCHEMICAL DEPOSITION REPAIR

3.1 Characterization Indicators

Electrochemical deposition is a new technology that emerged in the late 20th century for repairing concrete structure damage, particularly suitable for cases where traditional repair techniques are ineffective or costly. This method, widely used in metal materials, has seen active research in China in recent years for protecting metal and alloy materials. The principle of electrochemical deposition was first applied to concrete crack repair by Japanese scholars. In the late 1980s, the Japanese Port and Airport Research Institute and Mitsui Engineering & Shipbuilding Co. proposed the electrochemical deposition repair method for cracks in marine engineering (Sasaki et al., 1992).

Subsequently, Otsuki and Ryu (2002) applied this technology to land-based reinforced concrete structures, immersing pre-cracked reinforced concrete specimens in an electrolyte and applying a continuous current for 4-20 weeks. They evaluated the repair effectiveness through weight changes, crack closure, and surface coverage, also measuring water permeability, chloride ion penetration depth, and carbonation depth. The results showed that the deposition layer formed on the concrete surface effectively sealed cracks and formed a coating to prevent harmful component erosion. Initial cracks were typically induced by load, and Ryu (2001) evaluated the repair effectiveness of reinforced concrete with shrinkage cracks, immersing specimens with chloride-induced cracks in a $ZnSO_4$ solution for electrochemical repair for 8 weeks. The results indicated that electrochemical deposition repair technology not only sealed concrete cracks and reduced permeability but also positively impacted concrete desalination and steel reinforcement repassivation. Ryu (2005) induced cracks in concrete beams through loading, performed repairs, and then conducted flexural performance tests. The results showed that the repaired beams had higher flexural performance than unrepaired specimens. Zhang Qian (2022) characterized the repair rate by comparing ultrasonic pulse velocities before and after repair, finding that after 30 days of repair, the repair rates of the specimens reached 26.6%, 32.1%, and 35.0%, respectively.

3.2 Influencing Factors

Ostuki (Ryu & Otsuki, 2002; Otsuki et al., 2002) conducted experimental research on the selection of electrodeposition solutions using cement mortar specimens, testing eight solutions:$MgCl_2$、$ZnSO_4$、$AgNO_3$、$CuCl_2$、$CuSO_4$、$Ca(OH)_2$、$NaHCO_3$、$Mg(NO_3)_2$The results showed that no deposits formed on specimens in copper chloride, copper sulfate, calcium hydroxide, and sodium bicarbonate solutions; silver deposits formed only around cracks in silver nitrate solution; and more deposits formed on specimens in magnesium chloride, zinc sulfate, and magnesium nitrate solutions.

Domestic research on electrochemical deposition repair technology began in 2004. Jiang Zhengwu (Jiang et al., 2004; Jiang et al., 2006; Jiang et al., 2007) found that current density significantly affects repair effectiveness. Higher current densities produce larger but loosely arranged and lower-strength deposits, while lower current densities slow deposition but produce denser and higher-strength deposits. Additionally, using porous concrete to represent cracked concrete can effectively evaluate electrochemical repair effectiveness. Chu Hongqiang (Chu, 2005; Chu et al., 2010; Chu et al., 2010; Chu et al., 2009; Chu et al., 2005) conducted comprehensive research from various angles, including electrolyte type, repair device technical parameters, electrolyte temperature, concrete parameters, and post-repair cement matrix performance changes. He selected $ZnSO_4$、$MgSO_4$、$MgCl_2$、$CaCl_2$、$Al_2(SO_4)_3$、$Pb(NO_3)_2$ solutions for electrochemical deposition experiments, concluding that $ZnSO_4$、$MgSO_4$、$MgCl_2$as electrodeposition solutions, with appropriate experimental devices and parameters, achieve good electrodeposition results. He proposed multiple repair evaluation methods, such as mass increase rate and surface coverage, and found that adding additives to the electrolyte can adjust deposit morphology and deposition speed, inducing smoother and denser deposition layers, thereby reducing surface porosity and improving carbonation resistance. Specimens repaired with $MgSO_4$ showed better carbonation resistance than those repaired with $ZnSO_4$, and grey theory could more accurately predict the carbonation resistance of concrete after electrochemical deposition. Crack repair rates are generally faster in the early stages and slower later, with the rate change pattern independent of electrolyte type. Comparing repair rates under pulsed and direct current showed that pulsed current repair is more effective and can alter deposit morphology.

Li Senlin (2013) compared four anode materials: copper-clad niobium platinum wire, platinum-titanium composite wire, platinum-coated titanium wire, and platinum-niobium composite wire. The results showed that the platinum-niobium composite anode had relatively excellent electrochemical performance, minimal loss, and flexibility, making it suitable for bending and setting on different reinforced concrete components. It is an economical and high-performance anode material. Currently, most scholars directly use titanium mesh as the external anode, with limited research on anode material selection and mostly indoor experiments, resulting in relatively little research on anode arrangement methods.

Yao Wu (2005) studied the electrochemical deposition repair of concrete cracks from an electrochemical perspective, finding that current density concentrates at the crack tip, with the current density at the crack tip being hundreds of times higher than in adjacent undamaged areas. Li Shichao (2014) found that the closer to the cathode, the stronger the electric field, the higher the ion migration efficiency, and the easier the formation of deposits. He also proposed a formula for repair depth as a function of current and electrolyte concentration. Zuo Qingyuan (2020) added a surfactant, cetyltrimethylammonium bromide (CTAB), to the electrolyte to improve electrochemical deposition repair effectiveness. With a CTAB content of 2% in $ZnSO_4$ and $MgSO_4$.electrolytes, the results showed that CTAB improved surface coverage, crack healing rate, and permeability coefficient, enhancing the healing effect of electrochemical deposition repair. The composition of deposits in the cracks remained unchanged, but the microstructure became denser than without CTAB. Zeng (2022) added CTAB to the electrolyte in the range of 0.25%-2.00% in $ZnSO_4$ and $MgSO_4$.electrolytes. The results showed that with 1.00% CTAB, the bond strength between steel and mortar, chloride ion erosion resistance, and steel corrosion resistance were better after repair. Excessive CTAB weakened the repair effect. Deposit morphology was also affected by CTAB, but the composition remained unchanged.

Chu Hongqiang (2005) found that among three water-cement ratios, the mass increase rate and crack healing rate increased with the water-cement ratio, while surface coverage decreased with the water-cement ratio. This may be due to the increased porosity of mortar specimens with higher water-cement ratios. Among three protective layer thicknesses, the mass increase rate, surface coverage, and crack healing rate all decreased with increasing protective layer thickness.

Zhang Qian (2022) studied the effects of two conductive materials, carbon nanofibers and carbon black, on the electrochemical deposition repair rate and explored the interaction between these materials and cement concrete. The results showed that both carbon nanofibers and carbon black improved the electrochemical repair rate but reduced compressive strength. The improved repair rate was due to carbon nanofibers acting as micro-scale cathodes during electrochemical repair, enriching deposition sites and increasing the deposition product accumulation rate at cracks. Carbon black significantly reduced the resistivity of cement concrete materials, increasing the deposition rate on the concrete surface.

4.CONCLUSION

Electrochemical deposition repair technology can achieve crack repair, effectively preventing corrosive substances from diffusing into concrete, and can also achieve electrochemical chloride removal, restoring steel reinforcement to a repassivated state. This technology provides an efficient and environmentally friendly solution for concrete crack control, but further research is needed in deposition mechanisms, process optimization, and long-term performance. Future research should integrate materials science, electrochemistry, and artificial intelligence to build a "mechanism-process-performance" integrated research framework, promoting the large-scale application of electrochemical deposition in engineering and supporting the green transformation of civil engineering materials.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

COMPETING INTERESTS

Author has declared that no competing interests exist.

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