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Review Paper

Crack Repair in Existing Concrete Structures: Progress in Research and Applications

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Abstract: Concrete structures, among the most widely used building types, often develop cracks during construction and service due to factors such as construction quality, load effects, and environmental conditions. This review presents a thorough analysis of recent advancements in concrete crack repair, emphasizing the need for effective maintenance strategies in aging infrastructure. This paper integrates advanced laboratory research with real-world engineering applications to assess both conventional and innovative repair materials and methods, offering an overview of widely adopted techniques that provide valuable insights for researchers and practitioners aiming to enhance the durability and longevity of concrete structures.

Keywords: Concrete durability, Crack repair, Repair materials, Repair methods, Engineering applications.

1. Introduction

Concrete is one of the most widely used construction materials, renowned for its high compressive strength and durability. However, during both construction and service, factors such as quality control issues and environmental stresses can inevitably lead to the formation of cracks. As these cracks propagate, harmful substances from the surrounding environment can infiltrate the concrete, accelerating the deterioration of both the material and the embedded steel reinforcement. This process not only compromises the structural integrity but can also lead to catastrophic failure, resulting in significant economic losses.

Research has shown that concrete possesses some self-healing capabilities after cracking [1]. However, factors such as crack width, environmental humidity, and load conditions often prevent effective self-healing in many cases. In practice, most concrete structures remain cracked due to ongoing loading and environmental influences, with cracks progressively expanding over time. Once the crack width exceeds a critical threshold [2, 3], the structural durability deteriorates significantly. According to the "five-fold law," the cost of repairs increases exponentially with the time elapsed since the damage occurred [4]. Therefore, implementing proactive maintenance strategies and timely repairs is essential to mitigate the long-term impacts on aging infrastructure and reduce repair costs.

This paper examines the current state of research on repairing existing cracks in concrete, distinguishing passive repair strategies from self-healing approaches that incorporate bacteria or microcapsules during construction. As illustrated in Figure 1, it systematically addresses repair materials, traditional repair methods and novel repair methods, while offering detailed

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analysis based on cutting-edge laboratory research and engineering applications. The aim is to serve as a reference for future studies on concrete crack repair.

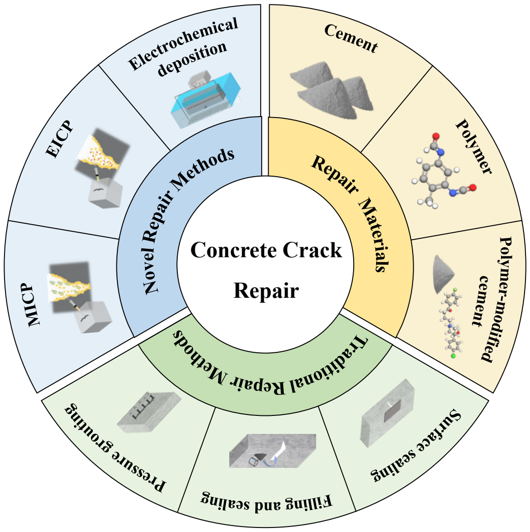

Fig.1 - Framework of the review

2. Repair materials

An ideal concrete crack repair material should exhibit excellent mechanical properties, including high strength and low shrinkage, while ensuring compatibility with the substrate. This ensures that the repair material can endure the stresses resulting from volume changes, chemical reactions, and electrochemical effects, without damage or deterioration over its design service life [5]. Therefore, selecting the appropriate repair material is critical to the success of crack repair. This section provides an overview of commonly used crack repair materials, including cement-based repair materials, polymer materials, and polymer-modified cement-based composites.

2.1. Cement–based materials

Cement-based repair materials offer several advantages, including excellent bonding properties, ease of application, low cost, and good compatibility with the substrate. These materials are the most commonly used in the repair of concrete structures. For cracks caused by steel reinforcement corrosion, cement-based materials can also cover the reinforcement surface, creating an alkaline environment that helps protect the steel. Common cement-based materials used for concrete crack repair include ordinary portland cement and geopolymer cement.

2.1.1. Ordinary Portland Cement

Ordinary Portland Cement (OPC) is the most widely used material for crack repair. As the primary binder in most concrete structures, OPC naturally exhibits compatibility as a repair material. However, OPC has several drawbacks, including slow setting and hardening, high shrinkage, and poor corrosion resistance. To improve the properties of OPC, various additives are often incorporated, such as fly ash and silica fume to enhance density and corrosion resistance, and polymers to improve tensile strength and impermeability. The key difference with polymer-modified cement mortar (PMC), introduced in Section 2.3, is that PMC involves the systematic incorporation of polymers into the cementitious mix to form a homogeneously distributed polymer network. This modification significantly improves properties such as flexibility, adhesion, and crack resistance. Typically, a small amount of polymer admixture is added directly to the OPC mix to enhance specific properties, such as reducing shrinkage or improving water resistance. Liu et al. [6] demonstrated that adding silica fume to OPC not only enhances the flowability of the repair mortar, but also significantly improves shear strength and reinforcement bond strength. In a project involving a floor slab with extensive through cracks, ultra-fine OPC grout was used for repair [7]. A small amount of styrene-butadiene emulsion was added to reduce cement shrinkage and improve water resistance. After repair, core samples were taken for splitting tensile strength testing, which met the required standards. Khayat et al. repaired cracks in a Canadian bridge abutment using OPC containing silica fume. Sonic tomography auscultation tests indicated that the cement grout provided effective repair, significantly enhancing the concrete properties of the abutment [8].

2.1.2. Geopolymer Cement

Geopolymer Cement (GPC) is a novel material developed by activating aluminosilicate precursors, such as fly ash, slag, metakaolin, phosphogypsum, and red mud, in an alkaline medium. Common activators include sodium hydroxide, sodium silicate, and sodium carbonate, which effectively reduce carbon dioxide emissions [9], making GPC a green, low-carbon binding material. GPC offers several advantages, including excellent bonding properties, high early strength, high density, and resistance to high temperatures [10], as well as acid and salt corrosion [11]. Furthermore, GPC's performance is similar to that of OPC, with comparable elastic modulus, Poisson's ratio, and other properties, making it an excellent material for crack repair.

Frasson et al. [12] pre-fabricated concrete specimens with a crack width of 2 mm and repaired them using GPC and epoxy resin. The compressive strength of the un-repaired specimens decreased by 13%, while the compressive strength of the GPC-repaired specimens decreased by only 3.7%. The repair performance was comparable to that of epoxy resin, demonstrating that GPC holds significant potential for concrete crack repair. Sun et al. [13] prepared geopolymer grouting material using industrial waste materials, such as fly ash and kaolin. In their study, a highway constructed in the early 21st century had been in service for 19 years when it developed extensive cracking under long-term traffic loads. After grouting repair, the deflection values for the transverse and longitudinal crack regions decreased by 23.6% and 26.9%, respectively, indicating that the cracks were effectively filled.

However, GPC faces challenges such as significant shrinkage. To mitigate this, researchers have incorporated additives, fibers, and gypsum to enhance its properties. A study by M. Palacios indicates that adding polyvinyl alcohol-based shrinkage reducers can reduce the shrinkage of geopolymer mortar by 85% and 50% under relative humidity conditions of 99% and 50%, respectively [14]. Additionally, research on the long-term performance of GPC is limited [15], and relevant industry standards are lacking, which makes large-scale applications still somewhat distant.

2.2. Polymer materials

Polymer repair materials are composed of high-molecular compounds that cure quickly, exhibit high strength, and provide good adhesion to cement-based materials. However, they face challenges related to poor compatibility, such as differences in thermal expansion coefficient and elastic modulus when compared to cement. Prolonged exposure to external environmental conditions can weaken the bond between polymer materials and cement substrates, potentially leading to delamination. Furthermore, polymers are susceptible to microbial growth, aging, and decomposition, and their high cost limits their widespread use. Commonly used polymer materials for concrete crack repair include epoxy resin and polyurethane.

2.2.1. Epoxy resin

Epoxy resin (ER) possesses excellent adhesive properties and can effectively bond with a wide range of construction materials, including concrete. It offers several advantages, such as high tensile strength, low shrinkage, and fast curing, while also restoring structural integrity, making it an ideal material for concrete crack repair. Standards have been introduced in China [16], the United States [17], and Europe [18] to guide the use of ER in repairing concrete structures. For instance, ACI 503.7 [19] provides comprehensive performance requirements and specific construction procedures for the application of ER in concrete crack repair.

Researchers have investigated the use of ER for repairing concrete cracks. Issa et al. [20] prefabricated concrete specimens with cracks of varying depths and repaired them using gravity-fed ER injection, comparing the mechanical properties of the concrete before and after repair. Compressive strength tests indicated that the epoxy repair method restored approximately 30% of the original compressive strength. Saliah et al. [21] induced 0.3 - 1 mm cracks in pre-loaded concrete beams and subsequently repaired the cracks with ER. Compared to the unrepaired control group, the epoxy repair increased the ultimate load capacity of the beams by 15%. In practical engineering applications, ER not only seals cracks but also reinforces and strengthens the structure. For example, the Zhen Tou Bridge in Liuyang City, Hunan Province, completed in 1976 [22], developed large cracks in the bridge deck and arch due to increasing traffic and prolonged service life. After repairing the cracks with ER, the strain at the top of the arch decreased by 23 με compared to before the repair.

However, ER has certain limitations, including susceptibility to aging, potential toxicity, and poor compatibility with cement-based materials. Studies have shown that after 1,500 hours of ultraviolet (UV) exposure, the tensile and flexural properties of ER decrease by approximately 10% and 29%, respectively [23]. To improve its weather resistance, researchers have modified ER with fluorinated graphene, demonstrating that its UV absorption capacity can increase to 785% of its original level [24].

Additionally, bisphenol A, the primary raw material in ER, is considered potentially carcinogenic and may pose risks to reproductive health [25]. In recent years, bio-based ERs have gained significant attention for their environmentally friendly properties. Compared with conventional ER, bio-based alternatives generally offer lower toxicity, greater toughness, and improved degradability, making them highly promising for applications in green buildings and sustainable materials [26,27]. Therefore, enhancing the aging resistance of ER while promoting the development of environmentally sustainable and cost-effective alternatives will remain a key research focus, potentially enabling broader applications in engineering fields.

2.2.2. Polyurethane

Polyurethane (PU) is a polymer that contains isocyanate groups (NHCOO-) in its molecular structure. It exhibits excellent properties, such as high adhesive strength, fast curing time, and good weather resistance [28]. When exposed to water, PU expands rapidly and reacts to form a flexible, foam-like substance, which can be used to fill wet cracks or even those with water flow. As a result, PU is widely used in the repair of seepage issues in dams and basements. In China, the first PU water-blocking chemical grouting material, named Cyanogen, was developed in 1973 [29]. With ongoing technological advancements, various PU grouting materials for different working conditions have been developed and widely applied.

De Belie [30] prefabricated concrete specimens with crack widths of 0.1 mm and 0.3 mm using steel plates and then injected a two-component PU into the cracks. After the repair, rapid chloride ion migration tests were conducted. The results indicated that the PU repair was effective, with the chloride ion resistance of the specimens with 0.1 mm and 0.3 mm crack widths recovering 83% and 67%, respectively. In a residential basement in Guangzhou, large cracks appeared on the exterior walls and floors during construction due to high temperatures, resulting in seepage problems [31]. PU was injected under pressure into the cracks, and the grout hardened rapidly, filling the cracks and completing the waterproofing. Subsequent tests confirmed that the basement remained dry with no damp spots, meeting the design waterproofing requirements.

In conventional industries, PU production heavily depends on petrochemical derivatives, generating isocyanates, phenols, and other toxic by-products [32]. Exposure to these toxic substances may lead to respiratory diseases, such as asthma, while the persistence of PU in soil can contribute to microplastic contamination [33]. In recent years, researchers have developed bio-based polyurethanes from vegetable oils, cellulose, and other renewable resources, aiming to lower production costs and reduce environmental pollution [34]. Pan et al. [35] reported that PU derived from soybean oil exhibited strong adhesion to concrete, with an interfacial tensile strength of 4.56 MPa and a shear strength of 21.73 MPa. This bio-based polyurethane holds significant potential for widespread application in concrete crack repair.

2.3. Polymer–modified cement–based materials

Polymer-modified cement-based composites (PMCs) are produced by incorporating specific polymers, such as ER, acrylic acid, and others, into cement-based materials [36]. These materials are commonly referred to as polymer-modified mortars (PMMs). The inclusion of polymers improves the microstructure of the cement matrix, enhancing its density. PMMs combine the advantages of both cement-based and polymer materials, offering benefits such as good compatibility with the cement matrix, high tensile strength, excellent bonding properties, and corrosion resistance. Currently, epoxy resin mortar is one of the most commonly used PMMs for concrete crack repair.

Epoxy resin mortar (ERM) is prepared by mixing epoxy resin, cement, sand, and additives in specific proportions. It exhibits high tensile strength, high flexural strength, excellent bonding properties, and is easy to apply. Additionally, ERM made with epoxy resin emulsion can be used for crack repair in damp environments, enhancing its versatility. Kan et al. [37] utilized ERM to repair cracks in concrete beams and found that the repair efficiency of the beam's bending load capacity increased with the addition of sand. When the sand content was 40%, the recovery rates for bending load capacity in beams with crack widths of 5 mm and 10 mm were 127% and 178%, respectively. ERM has demonstrated effective results in practical engineering applications for crack repair. For example, in a high-rise building in Changsha, Hunan Province, longitudinal cracks ranging from 500 mm to 2000 mm appeared on the side of the conversion layer beams [38]. The investigation revealed that these cracks were caused by significant temperature differences between the inner and outer parts of the concrete during pouring, but did not affect structural safety. To ensure suitability and durability, ERM was used to fill and seal the cracks. Subsequent inspections and monitoring showed no abnormalities, confirming the success of the repair.

ERM is widely used in practical engineering applications, however, some issues persist. On one hand, the high epoxy resin content in the mortar results in elevated costs. On the other hand, studies have shown that ERM is prone to aging when exposed to prolonged ultraviolet (UV) radiation, leading to a degradation in its mechanical properties [39,40]. Additionally, the performance of ERM is influenced by various factors, including the composition and dosage of epoxy resin, the cement composition, additives, temperature, and curing time. Therefore, further research is essential to optimize the mix proportions, reduce costs, and facilitate its broader application.

3. Traditional repair methods

Over the decades, traditional concrete crack repair methods have been central to infrastructure maintenance, defined by well-established techniques and standardized procedures. Techniques like surface sealing method, filling and sealing method and pressure grouting method are thoroughly documented in engineering codes [16,41], ensuring consistent application across various scenarios. These established methods deliver reliable performance, making them a preferred solution for structural damage repair and extending the service life of concrete structures.

3.1. Surface sealing method

The surface sealing method involves applying a sealing material to the crack surface to effectively close the crack. The repair process is as follows:

(1)Before repair, remove any loose debris from the crack surface and ensure it is clean and dry.

(2)Next, evenly apply the sealing material to the crack surface, ensuring it is smoothed out. The specific thickness and coverage area should be determined based on the construction plan and the repair materials used.

This method is simple to execute and requires minimal skill from workers. Common sealing materials include ERM, cement mortar, polyurea coating, and polymer mortar containing penetrating crystalline materials.

In a project's basement [42], significant temperature fluctuations between day and night during the pouring process, coupled with improper curing, led to the development of numerous fine shrinkage cracks and network-like cracks (width < 0.3 mm) on the exterior walls, which notably impacted the building's usability. Following an investigation, it was decided to apply polymer mortar for surface sealing of the cracks. Post-repair observations indicated effective crack sealing, and the usability requirements were successfully met.

However, this method is limited by its relatively shallow repair depth. The bonding strength between the repair material and the concrete substrate is crucial for the effectiveness of the repair. Prolonged exposure to temperature fluctuations and sunlight may cause the material to detach, necessitating regular inspections and replacements.

3.2. Filling and sealing method

Compared to the surface sealing method, the filling and sealing method has a broader range of applications. It is effective for repairing cracks with larger widths, through cracks, or even active cracks. The typical repair process for the filling and sealing method is as follows:

(1)Pre-repair: Cut a "V"-shaped groove along the crack, ensuring that both the width and depth fall within the range of 20 mm to 30 mm.
(2)Cleaning: Clean any grease, loose material, and debris from the crack groove to ensure proper bonding.
(3)Filling: Use an appropriate filling material to seal the crack, ensuring the surface of the filling is flush with the surrounding crack surface.

Common crack-filling materials include ER, PU, and polymer cement mortar. In a residential building project [43], vertical cracks appeared in the middle span of a beam due to improper construction practices. These cracks required repair. Construction workers cut grooves along the crack's path and then filled them with epoxy resin to seal the cracks. Subsequent tests showed that the repair met the normal usage requirements.

However, the filling and sealing method has a weak interface issue between the old and new materials [44]. Studies have shown that when the repaired area is subjected to loads, such as in the case of active cracks, the interface is prone to failure [45]. Therefore, before repair, the interface performance between the repair material and the base material must be carefully considered. Specific requirements should be set for the compressive strength, elastic modulus, and other properties of the repair material [46,47]. Additionally, the filling method involves cutting grooves into the crack, which can cause secondary damage to the structure. This method may not be suitable for cracks in critical load-bearing areas.

3.3. Pressure grouting method

The pressure grouting method can be used to repair most types of cracks, offering high repair efficiency. However, compared to the previous two methods, it requires more advanced construction equipment and skilled operators [48]. The typical repair process for the pressure grouting method is as follows:

(1)Pre-repair: Clean the crack surface to remove dust and loose materials, ensuring that the area on both sides of the crack, at least 50 mm wide, remains clean and dry.
(2)Spacing of Grouting Nozzles: Determine the spacing of the grouting nozzles based on the crack's width and depth. The typical spacing is between 200 mm and 300 mm.
(3)Sealing the Crack: Use materials such as epoxy sealants to seal the crack, creating an airtight cavity while leaving inlets and outlets for the grouting material.
(4)Pressure Leak Testing: After the sealant has reached a certain strength, conduct a pressure test to check for any leaks.
(5)Grouting: After cleaning the crack, use grouting equipment to inject the material from the bottom up until the crack is completely filled. The grouting pressure typically ranges between 0.2 MPa and 0.3 MPa.
(6)Post-grouting: Once the grouting material has solidified, remove the equipment and clean the crack surface.

Grouting materials can be classified into cement-based and chemical-based grouts. Cement grouting involves using neat cement slurry or mortar as the grouting material. The injectability of cement grouting is determined by the ratio of the maximum particle diameter of the cement to the average crack opening [8]. It is generally considered that cement grouting can only be used for cracks that are at least 1.5 to 2.3 times the maximum size of the cement particles [49]. Therefore, the permeability of the grout can be improved by reducing the cement particle size, such as with ultrafine cement, which is widely used for crack repair and reinforcement [50]. Chemical grouting typically uses materials such as ER, PU, and other substances with good fluidity and low viscosity, making them suitable for filling and repairing narrower cracks.

Wu et al. [51] developed a polymer-based composite material, which was successfully used for pressure grouting to repair cracks in a highway. Monitoring over 18 months showed that, under long-term traffic loads, the surface of the repaired area showed only minor wear, and the bond between the repair material and the base material remained strong, demonstrating the effectiveness of the repair.

4. Novel repair methods

In recent years, advancements in interdisciplinary research and technological innovation have led to the development of novel concrete crack repair methods. Techniques like microbially induced calcium carbonate precipitation (MICP), enzyme-induced calcium carbonate precipitation (EICP), and electrochemical deposition overcome limitations of traditional methods. Although these methods are predominantly studied in laboratory settings and their engineering applications remain limited, they show significant potential to improve efficiency, sustainability, and durability, marking a breakthrough in concrete crack repair.

4.1. Microbially induced calcium carbonate precipitation (MICP) method

Microbially induced calcium carbonate precipitation (MICP) is a method inspired by the natural process of microbial mineralization, wherein microorganisms interact with their environment to produce calcium carbonate. The most commonly used microorganisms are urease-producing bacteria, which generate urease to decompose urea into CO_2 and NH_3. The ammonia (NH_3) dissolves in water, making the solution alkaline, while CO_2 is converted into carbonate ions (CO_3^{2-}) in this alkaline environment. The negatively charged surface of the bacteria attracts calcium ions (Ca^{2+}), ultimately leading to the formation of calcium carbonate precipitation around the bacteria, which act as nucleation sites.

MICP has been extensively studied for concrete crack repair [52–55]. Compared to traditional concrete repair methods, MICP offers several advantages, including broad applicability, simple operation, and low environmental impact, making it a promising approach for further development. The main steps of the MICP process for concrete crack repair are illustrated in Figure 2:

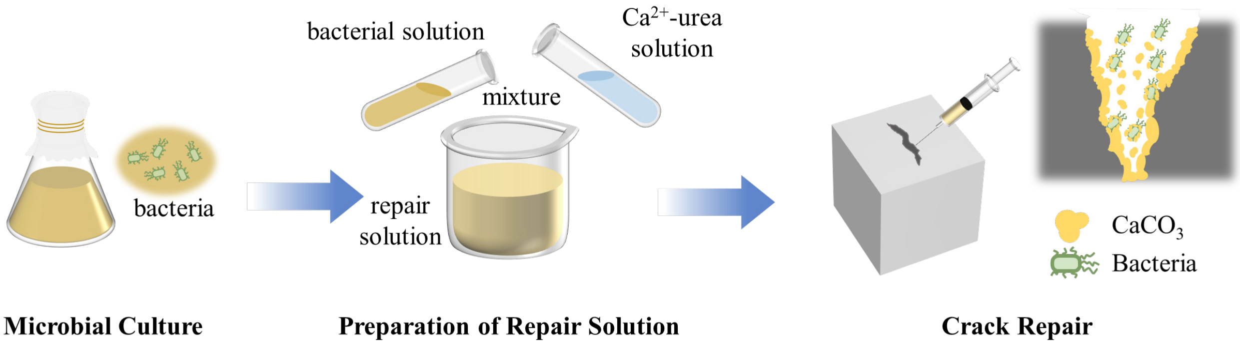

Fig. 2- Schematic diagram of MICP crack repair process

(1)Microbial Culture: Cultivate the microorganisms to obtain a microbial solution.

(2)Preparation of Repair Solution: Mix the microbial solution with a calcium source and urea to obtain the repair solution.

(3)Crack Repair: Use gravity infiltration, injection, or other techniques to fill the cracks with the repair solution and complete the repair.

De Belie et al. [56] investigated the repair of concrete mortar cracks using Bacillus sphaericus, employing silica gel to immobilize the bacteria and prevent the negative effects of the highly alkaline environment in the mortar. The results demonstrated that, when protected by the silica gel, the bacteria were able to produce calcium carbonate precipitation within the cracks, effectively filling them. Qian Chunxiang et al. [57] used agar to immobilize carbonic anhydrase-producing bacteria for concrete crack repair. After treating the samples with a coating, the initial water absorption rate decreased by up to 90%, showing effective repair for cracks less than 100 μm in width.

In practical engineering applications, reports have shown that MICP has yielded positive results in concrete crack repair. For example, in a residential area in Jinan, cracks in the underground garage walls led to severe leakage. The cracks were successfully sealed using MICP grouting [58]. Four months after the repair, a water injection test was performed on the cracked area, and no water seepage was detected. Core sampling revealed that the cracks were effectively filled with calcium carbonate, confirming the success of the repair. Wiktor et al. applied MICP to a parking lot floor slab in the Netherlands, where severe leakage had occurred. The results showed that the cracks were effectively sealed, the seepage problem was resolved, and the freeze-thaw resistance of the repaired area was improved [59].

However, MICP is influenced by various factors, such as microbial species, patch ratio, pH, and temperature, which can significantly impact the efficiency of crack repair. For instance, oxygen concentration affects the metabolism of aerobic microorganisms, potentially limiting the depth of crack repair [60]. pH and temperature not only influence bacterial activity but also affect urease function and the morphology of calcium carbonate crystals, which in turn impacts the effectiveness of crack repair [61,62]. The environmental pollution caused by ammonia by-products remains unresolved [63]. To reduce ammonia emissions, studies have explored the use of calcium acetate as a calcium source and the addition of zeolite or phosphate to mitigate environmental pollution [64-66]. Additionally, research on the long-term performance and durability of MICP is lacking, and these concerns must be addressed for its large-scale application. Therefore, further studies are needed to overcome these challenges and enable the widespread use of MICP.

4.2. Enzyme–induced calcium carbonate precipitation (EICP) method

Building on the research into MICP, researchers have developed the enzyme-induced calcium carbonate precipitation (EICP) method, which directly extracts relevant enzymes from microorganisms and plants. Compared to MICP, EICP eliminates the biological safety concerns and the high cultivation costs associated with microorganisms. However, commercial urease remains relatively expensive. To mitigate costs, scholars have successfully extracted urease from sources such as jack beans [67,68] and watermelon seeds [69,70], achieving favorable results. Additionally, to enhance calcium carbonate yield and improve crack repair efficiency, some studies have introduced additives like defatted milk powder and sucrose [71,72], which promote calcium carbonate production. These substances serve as nucleation sites or help stabilize urease activity.

The process of EICP for repairing concrete cracks is outlined in Figure 3 and follows these steps:

(1)Urease Extraction: Urease is extracted from plants such as soybeans and watermelon seeds.

(2)Preparation of Repair Solution: The urease solution is mixed with calcium sources and urea to prepare the repair solution.

(3)Crack Repair: The repair solution is applied to the cracks through methods such as gravity infiltration or injection, completing the repair.

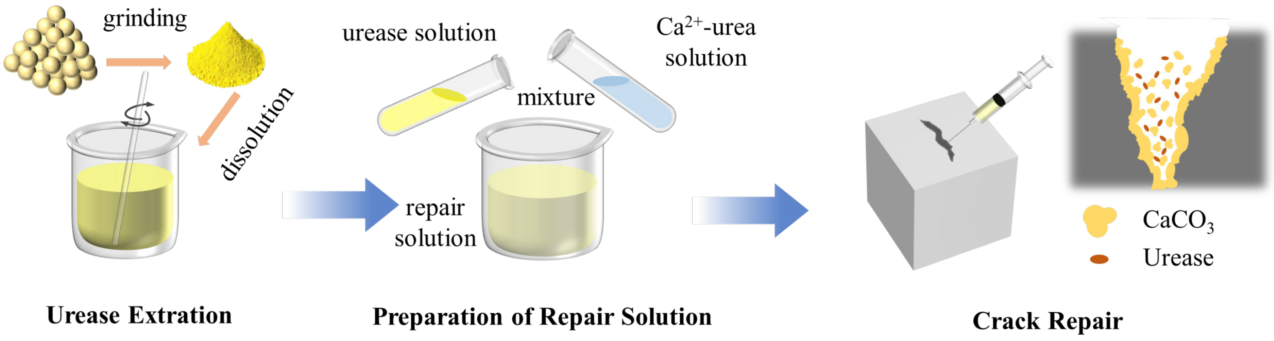

Fig. 3- Schematic diagram of EICP crack repair process

Dakhane et al. [73] successfully repaired mortar specimens with cracks using EICP. The flexural strength of the specimens increased by 33% compared to the control group, and there was a positive correlation between fracture toughness and the amount of calcium carbonate formed in the cracks. Zhu Jiahua [74] conducted laboratory research on EICP for repairing concrete cracks. By controlling factors such as urease concentration, types of calcium sources, and chitosan additive content, the crack repair effectiveness was significantly improved. This technique was successfully applied to repair cracks in a highway tunnel in Yunnan Province. Three months after the repair, no significant water leakage was observed. Ground-penetrating radar images revealed dense filling at the crack site, indicating favorable repair outcomes.

Compared to MICP, EICP effectively addresses the uncertainties and challenges related to microorganisms. The use of crude plant-derived urease also significantly reduces costs, making it more suitable for large-scale applications. However, EICP faces several challenges, including uneven distribution of remediation products, contamination from ammonia and nitrogen by-products, and insufficient nucleation sites. To tackle these issues, relevant studies have been conducted. Research indicates that adjusting the pH of the urease solution can significantly enhance the uniformity of calcium carbonate distribution [75]. Additionally, the strategies for reducing ammonia emissions discussed in section 4.1 of this paper are also applicable to EICP. Moreover, researchers have achieved better outcomes by incorporating skim milk powder and chitosan as nucleation sites [76,77].

4.3. Electrochemical deposition method

For concrete structures in hydraulic and marine engineering applications exposed to seawater environments, traditional repair methods may no longer be effective [78,79]. In response, researchers have developed electrochemical deposition technology, which offers several advantages over conventional repair techniques. These include a wide range of applicable scenarios, high repair efficiency, ease of operation, and cost-effectiveness [80].

The principle of electrochemical deposition is illustrated in Figure 4. In this method, mineral ions (such as Ca^{2+}, Mg^{2+}, and Zn^{2+}) in solutions or seawater serve as electrolytes, with the reinforcing steel inside the concrete functioning as the cathode. An auxiliary electrode is placed near the concrete to act as the anode. When an electric current is passed between the anode and cathode, cations (e.g., Ca^{2+} and Mg^{2+}) migrate towards the cathode under the influence of the electric field, where they precipitate and form solid deposits within the concrete cracks. These precipitates not only help protect the steel reinforcement from corrosion but also fill the cracks, effectively repairing the concrete structure.

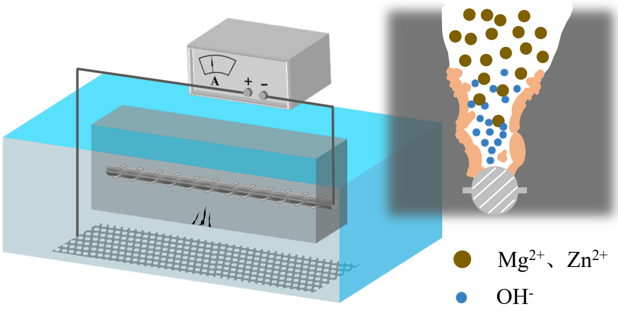

Fig. 4 - Mechanism of electro-deposition method

Ryu and Ostuki were among the first to demonstrate the feasibility of using the electrochemical deposition method for repairing concrete cracks in laboratory experiments [81]. While the deposited products filled the cracks, they also contributed to the repassivation of the steel reinforcement. Jin Weiliang and his team at Zhejiang University [82] investigated the effect of different current densities on the depth of crack repair using $ZnSO_4$ as the electrochemical deposition solution. The results showed that as the current density increased, the crack repair depth decreased. Microscopic analysis of the precipitates in the crack region revealed that, at low current densities, the precipitate density was higher, with smaller particles arranged more compactly. Therefore, selecting the appropriate current density is crucial to ensure repair efficiency when employing this technique. Chu et al. [83] found that, in addition to filling the cracks, the electrochemical deposition products also accumulated at the interface between the aggregate and mortar, improving the transition zone between them.

Most studies on electrochemical deposition have involved immersing concrete in an electrolyte solution for repair, which presents certain limitations. Chen et al. [84] suspended an electrolyte containing aluminum sulfate and calcium acetate in the crack region. Under the influence of an electric current, calcium vanadate was synthesized in situ to repair the cracks. This method not only accelerated the repair process but also expanded the potential applications of electrochemical deposition technology.

A concrete building [85], which had been in use for 35 years, developed cracks in its roof railing due to long-term carbonation corrosion, with widths ranging from 0.5 to 1.2 mm. Researchers used the electrochemical deposition method to repair the cracks in situ. After two weeks of treatment, the electrochemical deposition products had evenly formed in the cracks, almost completely sealing them. Additionally, the steel reinforcement within the cracks underwent repassivation, demonstrating the effectiveness of the repair. However, several issues remain that require further resolution:

(1) Several factors influence the effectiveness of electrochemical deposition repair, including the type of electrolyte [86], current density [87–89], repair time [90], and temperature, all of which require further study. For example, different anions directly affect the composition of deposition products [91]. Additionally, optimizing energization time and current density is essential to prevent resource wastage.

(2) Electrochemical deposition typically utilizes the reinforcing steel in concrete as the cathode. However, in structures with unexposed reinforcement, destructive measures such as drilling are required, potentially causing additional structural damage. Moreover, existing evaluation methods, such as visual inspection and water penetration tests, are limited, particularly for hidden structures. Developing non-destructive, effective testing methods is necessary. Huang et al. [92] demonstrated the potential of electrochemical alternating-current impedance spectroscopy in laboratory studies, achieving promising results for practical applications.

(3) While electrochemical deposition is effective, it may also negatively impact steel and concrete. Excessive current density can increase hydrogen generation at the reinforcement, raising the risk of hydrogen embrittlement [93]. Furthermore, electrochemical deposition may alter the bond performance between reinforcement and concrete. Wang [94] noted that the inorganic salts produced tend to form porous and low-density deposits, which could weaken the bond. This finding aligns with Chang's pullout test results, which indicated a 40–60% reduction in bond strength after electrochemical treatment [95]. In contrast, Qu et al. [96] observed an increase in bond strength due to higher sodium silicate content in the concrete. These discrepancies may stem from variations in current density and ion composition within the concrete, necessitating further research on the impact of electrochemical deposition on the steel-concrete interface.

5. Conclusions

This review summarizes recent advancements in concrete crack repair, focusing on the performance characteristics of repair materials, traditional repair methods, and innovative novel technologies.

Cement-based materials are cost-effective and compatible with concrete substrates but are constrained by low tensile strength and susceptibility to shrinkage. Polymer-based materials, such as epoxy resin and polyurethane, offer superior mechanical strength and flexibility, making them ideal for sealing and filling, though challenges remain regarding cost and environmental impact. Polymer-modified cement-based materials provide a balanced approach, combining enhanced tensile strength and chemical resistance. However, broader applications require further optimization.

Traditional repair methods, including surface sealing, filling and sealing, and pressure grouting, remain crucial in practical applications. Surface sealing is effective for shallow cracks but relies on adhesion and environmental conditions for durability. Filling and sealing methods are suitable for deeper cracks but are susceptible to interface failure under stress. Pressure grouting is an efficient solution for repairing various cracks but requires skilled operation and specialized equipment. Although each method is proven reliable, there are opportunities for enhancing durability, adaptability, and reducing secondary impacts.

Novel approaches, such as MICP, EICP, and electrochemical deposition, present alternative solutions but encounter practical challenges. MICP's performance depends on factors like microbial species and solution composition, while ammonia byproducts raise environmental concerns. EICP, which utilizes plant-derived urease, addresses certain cost and biosafety concerns but needs further optimization to improve product distribution and mitigate nitrogen pollution. Electrochemical deposition provides unique benefits for underwater repair but demands further optimization in areas such as electrolyte selection, current control, and impacts on the steel-concrete interface.

To date, studies on the long-term performance of crack repair remain limited, particularly for emerging methods like MICP, which are still far from widespread adoption and the establishment of relevant standards. Long-term on-site monitoring studies are crucial to address this gap. Additionally, future advancements in concrete crack repair should aim to integrate traditional methods with innovative technologies, with an emphasis on efficiency, sustainability, and cost-effectiveness. These efforts will pave the way for reliable, eco-friendly repair systems that ensure the long-term resilience of infrastructure.

CRediT authorship contribution statement:

Hui Zhao: Conceptualization, Methodology, Writing - original draft;
Yuxi Zhao: Conceptualization, Methodology, Supervision, Writing - review & editing;
Yunyun Tong: Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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