Opinion Article

Advances and Future Prospects in Microbial Repair of Concrete Cracks

Abstract: Concrete crack issues have always been the focus of attention in the field of civil engineering due to their direct impact on structural stability and durability. While some traditional repair methods are effective, they also possess numerous limitations. In contrast, microbial repair technology, apart from enhancing structural bearing capacity and durability, boasts environmental-friendly characteristics.This paper reviews recent research on microbial-based concrete crack repair, analyzing key aspects such as microbial species, repair mechanisms, methods, influencing factors, and characterization techniques. The aim is to provide new perspectives and ideas for future research.

Keywords: Concrete cracks; Microorganisms;Repair mechanism;Repair methods.

1. Introduction

Concrete, as a material widely used in modern construction, has long faced the issue of cracking. Cracks not only detract from the aesthetics of a building but, more importantly, can compromise the durability and safety of its structure. Traditional crack repair methods, like surface treatment, filling, and grouting, have limitations and may involve harmful chemical agents. In recent years, with the rapid development of biotechnology, microbial repair technology has gradually come into the spotlight. This technology leverages the metabolic activities of microorganisms, which can produce inorganic precipitates such as calcium carbonate through microbial mineralization and precipitation, filling cracks and thus repairing concrete cracks. Compared to traditional repair methods, microbial repair technology offers advantages such as ease of construction, low cost, and environmental friendliness without pollution.

Research results from 1973 found that some bacteria living in nature can utilize their metabolism to produce crystalline precipitates forming calcium carbonate[1]. With numerous scholars devoting themselves to research, MICP technology has come into people's view.

2.Microbial-Induced Calcium Carbonate Precipitation (MICP) Technology

MICP technology primarily leverages the generation of calcium carbonate precipitates induced by microorganisms to repair concrete cracks. The main principle involves utilizing enzymes in the metabolic process of microorganisms to promote the formation of carbonate ions, simultaneously acting as nucleation sites to combine with calcium ions and produce calcium carbonate precipitates, thereby repairing cracks[2]. Many microorganisms in nature can generate calcium carbonate precipitates, and different microorganisms have different precipitation mechanisms. Currently, the main mechanisms for microbial production of calcium carbonate precipitates include photosynthesis for calcium carbonate deposition, urease catalysis for calcium carbonate deposition, carbonic anhydrase catalysis for calcium carbonate deposition, and aerobic respiration for calcium carbonate deposition[3].

Among them, the urease catalysis mechanism for calcium carbonate deposition is simple, easy to control[4], produces highly efficient urease, has a low free energy change in the urea hydrolysis reaction system, and exhibits high urea conversion efficiency, capable of producing a large amount of $CaCO_3$ precipitate in a short time. Extensive research has been conducted on MICP technology. Gollapudi[5] were the first to explore the application of microbial mineralization principles in the field of crack repair and verified its feasibility through experiments. Bang[6] were the first to apply microbial-induced calcium carbonate precipitation (MICP) technology to repair concrete cracks. They mixed bacterial solutions with sand to repair concrete cracks, and the microorganisms successfully produced precipitates in the cracks, effectively repairing the cracks and enhancing concrete strength.Based on this, LuP[7] utilized Bacillus sp. to repair concrete cracks. Through various evaluation methods such as strength testing and microstructure studies, it was proven that MICP (microbially induced calcite precipitation) technology can effectively repair concrete cracks and improve the mechanical properties and chloride ion penetration resistance of concrete. This provides a new, environmentally friendly method for concrete crack repair.

3. Repair Methods for Microbial-Based Concrete Crack Repair

There are two methods for microbial-based concrete crack repair: active repair and passive repair.

Microbial passive repair refers to the use of MICP technology to generate calcium carbonate precipitates in cracks after concrete cracking is detected to achieve the purpose of sealing. Methods for microbial passive repair of concrete cracks include injection, immersion, and spraying. The injection method involves using a syringe to inject a cementitious solution mixed with microorganisms, calcium sources, and nutrients into the interior of concrete cracks, allowing them to react and produce calcium carbonate precipitates within the cracks to seal them. The immersion method involves immersing concrete in a cementitious solution containing microorganisms and calcium ions. Concrete samples are fully immersed in a microbial solution containing calcium ions and nutrients. Reactions between microorganisms and calcium ions generate calcium carbonate precipitates in the concrete cracks, thereby filling them. The spraying method involves spraying a microbial solution and a cementitious solution containing calcium ions and nutrients onto the concrete surface to generate calcium carbonate precipitates on its surface and block cracks.

Microbial active repair differs from microbial passive repair in that this method involves incorporating microorganisms into concrete during the concrete preparation process. When concrete has not yet developed cracks, these microorganisms remain dormant in a dry, oxygen-depleted environment. Once cracks appear in the concrete, water and oxygen flow into the crack channels and activate the dormant microorganisms[8]. These activated microorganisms produce calcium carbonate through metabolism, filling the cracks and achieving self-repair of the concrete. However, the internal environment of concrete typically has a high pH value, posing a threat to the survival of microorganisms. Additionally, microorganisms require certain space and nutrients during growth and metabolism. Wang[9] prepared self-healing concrete by encapsulating bacterial spores in microcapsules. Experiments showed that the healing rate (48%-80%) and maximum healed crack width (970 μm) of samples containing bacterial microcapsules were significantly higher than those of the control group (18%-50%, 250 μm), with water permeability reduced by approximately 10 times. Wiktor[10] chose porous lightweight aggregates to immobilize a mixture of bacteria and lactate, and created cracks of 0.5 to 1 mm in the molded specimens, which were then immersed in water for curing and repair. The results indicated that mineralization after microbial immobilization was more efficient, with a maximum crack repair width of up to 470 μm, more than twice that of the blank control group. Based on this, expandable clay particles were selected as microbial carriers, and microbial activity inside the concrete was characterized by oxygen consumption. The results found that the microorganisms immobilized by expandable clay particles remained active after the concrete specimens were cured for several months. The above experiments demonstrate that immobilization technology effectively enhances the self-healing capacity of concrete, providing important reference for the application of MICP technology in the construction field.Therefore, a carrier is needed to adsorb the microorganisms. Immobilization technology selects carriers with abundant interconnected porous structures, such as microcapsules[9], ceramic aggregates, and diatomite[11], to provide microorganisms with sufficient growth space and necessary nutrient exchange channels, thereby promoting microbial growth and metabolic activities.

Researchers provide a relatively enclosed and stable microenvironment for microorganisms using immobilization, which can effectively reduce the damage to microorganisms from the external high-pH environment[10], thus ensuring their survival rate and activity.

4. FACTORS AFFECTING MICP EFFECTIVENESS

Microbial-induced carbonate precipitation (MICP) is a complex biochemical process, and its effectiveness is influenced by multiple factors. Studies have shown that the primary factors affecting microbial mineralization are reactant factors and environmental factors.

Reactants, mainly urea and calcium sources, play a crucial role, and how they are added is key to enhancing mineralization efficiency[13]. Urea is a necessary condition for microorganisms to secrete urease. Only when urea is present in the solution where microorganisms reside will they secrete urease. The concentration of urea has a significant impact on microbial mineralization[14]. Within a certain range, as the urea concentration increases, the mineralization effect also enhances. However, when the urea concentration is too high, the enhancement trend of the mineralization effect gradually slows down or may even decrease. This may be because high concentrations of urea can inhibit microorganisms, reducing their activity and metabolic rate, thereby affecting the mineralization effect. Therefore, it is necessary to control the amount of urea added in practical applications to achieve the best mineralization effect.

Calcium sources also have a significant impact on microbial mineralization, directly affecting the amount of calcium carbonate generated, crystal morphology, and mineralization rate. Different types of calcium sources can affect microbial mineralization effects[15], influencing the overall repair effectiveness. Thus, selecting the appropriate calcium source is a critical factor in optimizing microbial mineralization and enhancing concrete crack repair. Meanwhile, the concentration of Ca^{+} also influences precipitation effects[16]. An appropriate Ca^{+} concentration can provide nutrients necessary for microbial growth, promote microbial metabolic activity, and enhance microbial mineralization deposition capacity. This is because microorganisms undergo mineralization reactions with Ca^{+} during metabolism, generating mineralized products such as $CaCO_3$. These mineralized products fill the pores and microcracks in materials, improving their compactness and strength. However, when the Ca^{+} concentration is too high, it can inhibit microorganisms, reducing their activity[17], suppressing microbial growth and reproduction, and affecting microbial mineralization efficiency.MA[18] investigated the variations in Ca^{2+} concentration and calcium precipitation capacity in solutions with different calcium sources, and prepared microbial self-healing mortar specimens to study the impact of microbial repair agents containing various calcium sources on the strength of the mortar specimens. The results indicated that the mineralization mechanism of Bacillus subtilis differed under different calcium sources, leading to differences in mineralization capabilities. Additionally, the calcium source also influenced the flexural and compressive strength of the microbial self-healing mortar. When calcium lactate served as the calcium source, the repair effect on mortar cracks was the most effective, followed by calcium acetate and calcium nitrate.

Environmental factors also have a significant impact on microbial mineralization effects, primarily including temperature and pH value. These environmental factors influence microbial growth and metabolic activity, affecting microbial mineralization efficiency.

Temperature has a very significant impact on microbial growth and urease activity[19]. For example, the optimal growth temperature for urea-decomposing bacteria is usually between 20 and 40°C. Within this range, microbial urease activity is highest, accelerating the rate of urea hydrolysis to generate CO_3^{2-}, thereby promoting calcium carbonate precipitation. When the temperature is too low, low temperatures can reduce the enzyme activity within microbial cells, slowing down microbial growth rates and even potentially stopping growth. In addition, low temperatures can cause intracellular water to freeze, damaging microbial cell structures. When the temperature is too high, microbial proteins may denature, leading to cell death. High temperatures can also accelerate microbial aging and death processes, thereby reducing microbial mineralization effects.

Within an appropriate pH range, microbial metabolic activities and mineralization can proceed smoothly, promoting calcium carbonate deposition. The pH in concrete cracks can reach as high as 13[20], while the more suitable pH range for microbial-induced carbonate precipitation is between 7 and 9. Within this pH range, microbial urease activity is higher, effectively decomposing urea to produce carbonate ions, thereby promoting the formation of calcium carbonate precipitation. However, overly acidic or alkaline environments may inhibit microbial growth and metabolism, further affecting mineralization effects.MENG[21] further enhanced the activity of Bacillus pasteurii in high-alkali environments through gradient domestication. Compared to concrete samples with non-domesticated microorganisms, the compressive strength of concrete samples incorporating domesticated microorganisms increased by 16.59% after 28 days of curing, while the water absorption coefficient decreased by 37.74% and the permeability coefficient reduced by 19.22%. In crack self-healing tests, the maximum crack repair width achieved in concrete samples with domesticated microorganisms was 0.57 mm, exceeding the 0.44 mm observed in the non-domesticated microorganism group.

In the process of microbial mineralization to generate calcium carbonate precipitation, many factors can influence mineralization effects. Besides the aforementioned conditions, microbial species, microbial inoculum size, incubation time, and nutrient concentration can also affect mineralization effects. Therefore, in practical applications, it is necessary to comprehensively consider these factors to create optimal conditions for microbial mineralization, thereby achieving the best mineralization deposition effect.

5. Characterization Methods for Repair Effectiveness

The characterization methods for assessing the effectiveness of microbial mineralization technology in repairing concrete cracks encompass a comprehensive system including apparent observation, microscopic crystal morphology observation, permeability testing, depth repair detection, mechanical performance testing, and long-term performance evaluation. These methods collectively constitute a comprehensive framework for evaluating the repair effects of microbial mineralization technology on concrete cracks.

Apparent observation is an intuitive method to characterize the repair effectiveness of concrete cracks. Microscopes and other tools are typically used to track and observe the repaired concrete surface, documenting the crack repair status. The repair rate of crack width is an important characterization index, which is assessed by measuring the crack width at different time points and calculating the repair rate[22].

High-precision instruments such as scanning electron microscopes (SEM) can be used to observe the microscopic morphology of calcium carbonate and other products generated by microbial mineralization, including crystal shape, size, and distribution. This microscopic structural information aids in understanding the mechanism of microbial mineralization and characterizing the microstructural changes in repaired concrete cracks.

Permeability can characterize the impermeability of repaired concrete. Methods such as water absorption tests and impermeability tests can be employed to test the permeability of repaired concrete. By comparing the changes in permeability before and after repair, the effectiveness of microbial mineralization precipitation technology in enhancing the impermeability of concrete can be evaluated[23].

Depth repair detection is a method to characterize the repair effectiveness of internal concrete cracks. Since concrete cracks may extend deep into the concrete, non-destructive testing techniques such as ultrasonic testing and X-ray computed tomography (X-CT) can be used to inspect the repair status of internal cracks.

Mechanical performance testing can characterize the mechanical properties of repaired concrete. By testing mechanical performance indicators such as compressive strength and flexural strength[24] of repaired concrete, the restoration effect of concrete mechanical properties can be characterized.

Apart from these short-term performance evaluation methods, long-term performance evaluation of repaired concrete is also necessary. This includes assessments of resistance to carbonation, chloride ion penetration, and frost resistance. Through long-term observation and testing, the stability and reliability of repaired concrete during subsequent use can be evaluated.

6. Concluding remarks

With the advent of the concept of green building, people's demands for quality of life are increasingly high. Developing an efficient and environmentally friendly concrete crack repair technology is of great importance. Although microbial repair technology has achieved certain research results, there are still many issues that require further investigation. For instance, how to enhance the mineralization efficiency of microorganisms, reduce repair costs, and ensure repair quality. In addition, further exploring the survival and metabolic pathways of microorganisms in concrete, as well as the impact of environmental factors on microorganisms, is also crucial for optimizing repair effectiveness.

Addressing these issues, future research can be conducted from the following aspects:

Screening and optimizing microbial strains: By screening microbial strains with high mineralization capacity or modifying microorganisms through domestication, their mineralization efficiency and adaptability can be improved.

Researching novel microbial carriers: Combining new materials and technologies such as nanotechnology and biotechnology, more efficient and environmentally friendly microbial carriers can be developed to enhance repair quality and efficiency.

Studying the impact of environmental factors on microbial mineralization: In-depth research into the impact of environmental factors on microbial mineralization effectiveness can provide more accurate guidance for the practical application of Microbially Induced Calcite Precipitation (MICP) technology.

Strengthening long-term performance evaluation and monitoring: Conducting long-term performance evaluation and monitoring of repaired concrete can ensure the reliability of repair effects.

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