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Microbial-induced Deposition of Calcium Carbonate to Repair Concrete

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Abstract

With the rapid development of the construction industry, the service life of concrete buildings has been severely tested. Due to its characteristics, concrete cracks become inevitable in concrete structures. The existence of cracks seriously affects the durability and safety of concrete. The repair of concrete cracks is an urgent issue. The emerging MICP technology can repair concrete cracks by inducing the precipitation of calcite by microorganisms, which is more economical and environmentally friendly than the traditional crack repair methods, and thus has become a hot research topic in recent years. The influencing factors for the effect of bioremediation of concrete are also under constant research. This paper summarizes the current research status of MICP technology and the repair of concrete cracks. The mechanism of MICP is introduced, and the influencing factors of concrete crack repair are discussed.

Keywords

Concrete; Crack Healing; MICP; Influencing Factor.

1. Introduction

Concrete is one of the most used and widely used civil engineering materials in the world today[1]. Concrete, on the other hand, has inherent properties such as low tensile strength and brittleness that make cracks unavoidable in its concrete structure. Cracks allow water and chemicals to seep into the concrete, causing it to deteriorate. If cracks are not repaired promptly, they can expand and the enlarged cracks can jeopardize the durability of the concrete. In addition, repairing enlarged concrete cracks can lead to increased costs. Conventional concrete crack repair utilizes chemical sealers or surface treatments, which are time-consuming and have limitations. In recent years, the use of microorganism-induced calcite precipitation in concrete to repair cracks and improve their properties has become a hot research topic in recent years[2,3]. Reduce the potential for concrete erosion by filling pores and cracks in the concrete matrix with calcite precipitation.

Concrete contains a small amount of unhydrated cement fraction, which can continue to hydrate and carbonate in wet environments, which is beneficial for crack self-repair, however, this repair ability is minimal [4], Most of the cracks need to be repaired manually, which undoubtedly increases the maintenance cost of the project. In the MICP crack repair technology, the metabolism of urease-producing bacteria accelerates the deposition of calcium carbonate, and the generated products (e.g., calcite and spherulite, etc.) are compatible with the concrete matrix, which can prolong the service life of the concrete. Currently, the methods of repairing concrete cracks using MICP technology mainly include a grouting method and an embedding method. In the grouting method, the nutrient solution containing a sufficient amount of urease-producing bacteria is repeatedly filtered on the concrete cracks, so that biofilm is attached to the crack surface, and the microbial metabolism of the biofilm is utilized to accelerate the deposition of calcium carbonate. In some other studies, dormant microorganisms and their nutrients were implanted into concrete structures as self-healing agents, and the

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microorganisms could be activated and metabolized in the cracks to promote the production of calcium carbonate in the cracked area so that the cracks could be repaired in situ[5].

Microbial restoration of concrete, as an environmentally friendly technology, has a very promising application prospect. The urease-producing bacteria used in the existing studies are mostly pure strains such as Bacillus megaterium and Bacillus subtilis. It is worthwhile to study how to assemble microorganisms and their nutrients into self-healing agents to maintain good microbial activity in the strong alkaline environment of concrete crack solution and to obtain ideal repair effects. In addition, the fracture environment (pH of the fracture solution, Ca2+ concentration, CO32-, and nucleation sites)[6]. It has an important effect on the deposition of calcium carbonate and the efficiency of crack repair, and it is necessary to further study the repair effect of concrete cracks and the law of repair conditions.

2. Overview of Urease and Urease-Producing Microorganisms

2.1. Urease-Producing Microorganisms

Urease, also known as urease, is a nickel-containing oligomer that can specifically degrade urea and is found in microorganisms, plant seeds, animal blood, and urine[7].

Microorganisms have a high capacity to produce urease, and according to the known urease-producing microorganisms, it is known that their species cover the genus Fusarium (Fusarium oxysporum), Trichoderma (Trichoderma sp), Phialocephala, Colletotrichum (Colletotrichum graminicola), Paecilomyces (Paecilo–myces formosus), Providencia genus of bacteria (Prov–idencia rettgeri JN–B815), Bacillus (Bacillus amyloliquefaciens JP–21, Bacillus atrophaeus, Bacillus aryabhattai UR–F51), Sporosarcina (Sporoscarcina pasteurii YB–B, Sporosarcina pasteurii DSM33), Acinetobacter (Acinetobacter radioresistens), Raoultella sp. (Raoultella Ornithinolyt–ica), Pseudomonas (Pseudomonas putida DCB13), Agrobacterium (Agrobacterium tumefaciens OAH–01), Kocuria in actinomycetes (Kocuria flava) also found[8].

2.2. Application of Urease-Producing Microbes

Urease-producing microorganisms have broad application prospects in the fields of chemical industry, winemaking, medicine, ecological restoration, sewage treatment, building materials, and cultural relics restoration.

1) MICP technique

Microbially induced carbonate precipitation (MICP) is a natural process in which bacterial activity changes the supersaturation conditions of aqueous media, leading to the precipitation of carbonate minerals. Compared with the naturally occurring carbonate mineralization process, MICP occurs faster due to the action of bacterial enzymes. Microbial metabolic activities increase the pH of aqueous media and promote MICP through several pathways, including urea dissolution, sulfate reduction, iron reduction, and denitrification.

The precipitated calcium carbonate crystals can bind the soil particles together to increase the strength and stiffness of the soil while controlling a relatively high permeability. Compared with cement, the viscosity of the bacterial suspension is lower and can be injected into small pores or cracks in the structure, so that the precipitated crystals are filled into small cracks. Carbonate precipitates can also change the surface properties of oil-water separation materials and improve the separation efficiency. In addition, carbonate minerals can co-precipitate with heavy metals, increasing the solidification of contaminated soil. Carbonate precipitation is also an effective carbon sequestration method, making MICP widely used in geotechnical, environmental engineering, hydraulics, and other fields.

At present, MICP technology is widely used in the repair and reinforcement of building cracks[9]. At the same time, microorganisms can promote the formation of metal carbonates

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and reduce their migration and toxicity[10]. Therefore, it is feasible to use urease-producing microorganisms to immobilize heavy metals.

2) Treating Waste Water

Urea-producing microorganisms can treat urea wastewater, and compared with pure urease treatment technology, it is more perfect and economical and has the characteristics of simple operation, strong treatment capacity, and good treatment effect. This makes the activated sludge containing urease a promising method for treating urea wastewater.

3) Detoxification for liquor

Urea is an important source of carcinogen ethyl carbamate in wine. Urea-producing bacteria can effectively remove urea in wine and improve the quality of wine.

4) Treatment of Uremia

Uremia is a serious disease. When the patient's renal function is lost, his kidney cannot produce urine, which makes the body's metabolic waste such as urea unable to be discharged, thus causing certain harm to the body. The existing medical technology can not completely cure uremia, only through hemodialysis to prolong the life of patients. If this bacteria is introduced into the human body, it will be able to break down urea, to achieve the purpose of the treatment of uremia. In 1996, Prakash S genetically engineered urease-producing bacteria were introduced into the intestines of uremic rats with renal failure, confirming the feasibility of urease-producing strains for the treatment of uremia.

3. Research on MICP Repair of Concrete Cracks

Cracks are inevitable in the daily use of concrete. Cracks in concrete may reduce the service life of the concrete structure. There are several repair techniques available for repairing cracks, but they are costly and time-consuming. Self-healing concrete is a highly efficient and environmentally friendly repair method for self-healing cracks in concrete.

3.1. Mechanisms of Application in Concrete

Self-healing concrete is a mixture of enzymes or microbial biomass and inorganic matter produced through the process of microbial-induced calcium carbonate precipitation (MICP) [microbial-induced calcium carbonate precipitation in the surface or soil]. Calcium-based biocement consists of urea-producing bacteria (UPB) (e.g., Bacillus sphaericus), urea (CO(NH2)2), and soluble calcium salts (e.g., calcium chloride or CaCl2). UPB produces the enzyme urease, which converts urea to ammonium and carbonate ions. When calcium salts are added to the reaction, calcium carbonate (CaCO3) is formed. This biogenic CaCO3 binds loose particles together and plugs fine pores and cracks. The main chemical reactions of MICP are as follows:

$$CO(NH_2)_2 + 2H_2O + UPB \rightarrow 2NH_4^+ + CO_3^{2-} \quad (1)$$

$$Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3 \quad (2)$$

There are two main techniques for repairing concrete cracks using microorganisms. One is to produce cracks in concrete, through the grouting method in the loose aggregate in stages (batch) to add uniform bacterial solution and cementing liquid[11], to be repaired after the slurry is filled with cracks and hardened and the original structure of the concrete bonded together, to seal the cracks. Mostly used for structural impermeability requirements of high or high integrity requirements of structural crack sealing, and the repair effect is good. The cementing solution is a mixture of urea and calcium-containing substances, which acts as a source of

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calcium and carbonate in the process. Microbial mineralization deposition CaCO3 is more mobile before condensation and mineralization, and with the help of pressure can repair the deeper cracks, not only the cracks in concrete, but also in search of leakage in the effective sealing, which is very important for some complex crack repair work. Liang et al. in the use of the MICP grouting method When comparing different calcium sources, it was determined that the consolidation effect of calcium nitrate was more favorable.

The other is self-healing, in which microorganisms are loaded into carriers and used as raw materials to process concrete, allowing the resulting concrete elements to repair themselves after cracks occur[12]. There are many different carriers for microorganisms, but they can be broadly categorized into core-shell carriers and capsule carriers. In related research, low alkali cementitious materials, ceramics, porous glass particles, diatomaceous earth, expanded perlite, biochar, shale ceramic sand, expanded clay particles, coral reefs, regenerated bone, microcapsules, natural fibers, and hydrogels are used as microbial carriers to provide a suitable environment for microbes to grow in the cementitious materials and to release microbes after the formation of cracks in the concrete and guide the calcium carbonate precipitation to fill in the cracks and repair the cracks.

3.2. Effects of Encapsulated Microorganisms on Concrete Components

The addition of microbial encapsulants will affect the setting time of concrete components, different concrete components' encapsulant loading rates may have an impact on the setting time of the cement, if the setting time is too short, it will lead to the casting out of the concrete components of the integrity of the reduced.

Compressive strength is one of the most important indicators used in concrete for determining its properties and checking the correct production of concrete. As we know from previous studies, the compressive strength of hydraulic concrete specimens mixed with microorganisms decreases with the increase in the concentration of microorganisms, which was confirmed in the study of the effect of Bacillus megaterium on the compressive strength of concrete by Andalib[13] and others.

3.3. Factors Affecting Crack Repair

The addition of different calcium sources in the embedded body will affect the self-repairing performance of concrete components and the compressive strength after repair, under the same temperature conditions, the solubility of different calcium sources in the solution is not the same. In this process, due to the hydration reaction, the internal temperature continues to rise, and the internal temperature of the concrete can reach up to 80℃. The increase in temperature changes the solubility of the calcium source, which in turn affects the repair of cracks. The addition of calcium lactate delays the setting time of the concrete, while the addition of calcium formate and calcium nitrate accelerates the setting time[14].

Researchers have investigated whether early cracking and subsequent repair of concrete can help its mechanical properties[15]. A considerable number of studies have concluded that self-repair is more efficient in early life than in later life[16]. The effect of age on crack formation showed that young cracks healed completely, with a gradual decrease in healing efficiency. Similarly, the width of filled cracks decreases[17].

Water passing through concrete cracks can affect self-healing[18]. Several studies have shown that moisture is essential for self-healing. Common solvents cause chemical reactions in the binder matrix and transport fine particles to the crack surface. Studies have shown that calcite has a strong self-healing ability, which is influenced by external factors. The transport of water in the cracks and the growth of calcite precipitates have been studied, which contribute to the healing of the cracks[19]. On the surface of the fissure, water is absorbed and a thick layer of

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calcite is formed. As a result, the fissure cannot be completely closed in the depth direction. This property does not guarantee proper closure of the fissure[20].

4. Conclusion

The existence of concrete cracks seriously affects the service life and safety of concrete buildings. When repairing cracks, the emerging MICP technology has greater advantages than traditional repair methods. When MICP technology is applied to repair concrete cracks, different application mechanisms will produce different repair effects. At present, the available self-healing methods include a grouting method, direct addition of microorganisms, and carrier-loaded microorganisms. Among these methods, the grouting method is the most simple and easy to operate method, but its limitations are large, and it is impossible to repair the concrete cracks that are not found in time. Direct addition of microorganisms can be repaired in time. Still, in the face of a strong alkaline environment in concrete, some microorganisms are difficult to survive, resulting in greatly reduced repair efficiency. Compared with the previous two methods, the carrier-loaded microorganism method has both the timeliness and efficiency of repair. However, the development time is short, and the selection of carriers and embedding methods need to be optimized.

At the same time, it is necessary to further study the factors that affect the repair of concrete cracks, to ensure that the packaging self-healing technology is used in the real environment without adversely affecting the mechanical properties. The self-healing effect of concrete must be proved under harsh environmental conditions in practical applications.

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