Academic Journal of Science and Technology
ISSN: 2771-3032 | Vol. 4, No. 1, 2022

Research Status of Microbial-Induced Calcium Carbonate Precipitation Technology Applied to Self-healing Concrete

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Abstract: Microbial-induced calcium carbonate precipitation (MICP) is often used to improve the engineering properties of different building materials in recent years, which has great development prospects. This process takes advantage of the metabolic activity of microorganisms and eventually leads to the precipitation of calcium carbonate through changes in the microbial environment. The self-healing effect (SH effect) of microbial concrete can be explained as the ability to repair cracks in concrete by spontaneously generating biological stimuli by microorganisms to obtain CO_3^{2-} and react with Ca^{2+} in the material to form $CaCO_3$ crystals without any external or human intervention. This sustainable development project has replaced traditional techniques for the restoration of concrete.

Keywords: Self-healing, Microbiological technology, Concrete.

1. Introduction

Driven by extraordinary human technological progress, the concrete industry has made tremendous progress. Concrete is produced at a high rate each year, and since concrete production produces a large amount of carbon dioxide (about 8% of global carbon dioxide emissions), producing more sustainable concrete materials is critical [1]. Many researchers are devoted to the creation and application of microbial concrete, because of its ability to self-repair cracks, microbial induced calcium carbonate precipitation (MICP) soil improvement technology has attracted extensive attention. MICP has many advantages: simple construction method, almost no harmful substances; Less chemical pollution; Compared with the traditional chemical slurry, the concentration of bacteria liquid and bonding liquid is lower, and it is easier to penetrate into the geotechnical materials [1]. The durability and strength of concrete improved by MICP can be ensured [2]. However, it is often difficult for the used microorganisms to achieve the desired results in the repair process, which indicates that there are still many problems in the practical application of this kind of material. This paper DISCUSSES the principle of microbial-induced carbonate precipitation technology, the application status of this technology at home and abroad, and the factors affecting the effect of microbial cement remediation, so as to provide some references for the future theoretical research and practical application of microbial-induced calcium carbonate precipitation technology in concrete remediation.

2. Principle of Microbial Induced Carbonate Precipitation for Repairing Cement Materials

MICP is often used to improve the engineering properties of different building materials in recent years, which has great development prospects. This process takes advantage of the metabolic activity of microorganisms and eventually leads to the precipitation of calcium carbonate through changes in the microbial environment[3].

The crack repair capability of microbial concrete comes in two ways[4]. Firstly, the microorganisms can produce carbon dioxide or carbonate ions, then form calcium carbonate precipitates with chemical reacting. Concrete creates an alkaline environment for microbial activity, which facilitates calcium carbonate precipitation. Besides, microorganisms can take up cations from the environment, including calcium ions deposited on the cell wall surface, which react with carbonate ions, causing calcium carbonate to precipitate on the cell surface (see Eqs. 1 and 2)[5].

$$Ca^{2+}+Cell \rightarrow Cell\text{-}Ca^{2+} \quad (1)$$

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

Among the pathways of calcium carbonate precipitation caused by microorganisms in the natural environment, MICP via the uretization pathway is the most widely used. The advantages of this pathway are high efficiency and straightness, and it has been successfully used to improve the mechanical properties of cement[6]. During MICP, urease-producing microorganisms hydrolyze urea to form ammonium and carbonate ions, which then react with soluble Ca^{2+} to form $CaCO_3$[6] (see Eqs. 3 and 4).

$$Co(NH_2)_2+2H_2O \rightarrow HCO_3^{2-}+2NH_4^{+}+OH^{-} \quad (3)$$

$$Ca^{2+}+CO_3^{2-}+bacteria \rightarrow bacteria\text{-}CaCO_3 \downarrow \quad (4)$$

The self-healing effect (SH effect) of microbial concrete can be explained as the ability to repair cracks in concrete by spontaneously generating biological stimuli by microorganisms to obtain CO_3^{2-} and react with Ca^{2+} in the material to form $CaCO_3$ crystals without any external or human intervention[7]. This sustainable development project has replaced traditional techniques for the restoration of concrete.

3. Application Status of Microbial Concrete Self-healing Technology

According to the literature, there are two methods of applying microbial healing agents in concrete, which are direct application and sealing self-healing[7]. The former uses healing agents directly in concrete, incorporating microorganisms into light aggregate (LWA) and graphite nanosheets (GNP). The results showed that GNP was a good microbial carrier compound with good fracture healing effect. In order to meet the intensity requirement, the method needs to find the best microbial concentration, which is 30×10^5CFU /ml[8]. The latter is a lightweight aggregate impregnated with a microbial solution, which is then encapsulated in a polymer-based coating to improve the self-healing overall performance of concrete. For example, the microcapsule method is used to self-heal the material, and once the fracture destroys the embedded microcapsule, the healing agent is released to the crack surface by capillary motion. Sealing self-healing has high quality self-healing ability, which can heal a wider range of crack width and respond to cracks in the matrix earlier.

4. Factors and Requirements Affecting the Properties of Microbial Concrete Materials

Due to the unique precipitation activity of some microorganisms, microbial technology can improve the durability and mechanical properties of cement-based composites, such as compressive strength, permeability, porosity, etc[8]. At the same time, the microbial concrete technology is also limited by a variety of factors, such as the characteristics of the microorganism itself and the characteristics of concrete, etc., which will be discussed in the following aspects.

4.1. Microbial requirements for microbial concrete technology

The selected microorganisms must not only meet the basic conditions of the MICP process, but also ensure safe use in the environment. Vidakovich et al. stress that the selected microorganisms must not cause disease before, during, or after biological processes[9]. Microorganisms can be used in concrete to meet the following four conditions: a complete description of the characteristics (genetic changes and ecological characteristics of microorganisms, etc.); 2. The reproduction and application of microorganisms should follow the biosafety law (such as gene mutation); 3. The stability, activity, packaging and storage of microbial products shall comply with laws and regulations; 4. A thorough assessment of the health risks of microbial release into the environment[9]. Because MICP technology is very demanding for microorganisms, the cost in the application process is relatively high.

4.2. Effects of concrete environment on microbial remediation

The SH effect of microbial-based concrete is usually influenced by the variable environmental conditions in the concrete material. One, PH. Concrete usually provides an alkaline environment, but the PH varies greatly during its use. Over time, external environmental influences can decrease the pH to a value lower than 9[10]. Therefore, the MICP process usually takes place in alkaline environments, which means that alkali tolerant or alkalophilic bacteria are able to exhibit greater repair capacity during the SH effect[10]. Besides, the migration of calcium sources, especially to cracks, is under the dissolution of microorganisms. Because high concentrations of calcium can limit microbial activity, a free calcium value of 0.25M is considered the best choice for SH effect[11]. Calcium leaching and cracks in concrete often occur at the same time, so in concrete pores, free Ca^{2+} concentration is low, suitable for microbial activity. Third, there are some elements in concrete matrix that affect the activity of microorganisms. Although 80% of the concrete composition has no effect on microbial activity, there are still some elements that may stimulate or inhibit microbial activity. From the perspective of microbial activity, Na^+, Mg^{2+}, K^+ and Cl^- did not affect the microbial activity, while Mn^{2+} might lead to the reduction of microbial activity, and Li^+, Zn^{2+} and Ba^{2+} could increase the microbial activity[10].

In addition, there are many different environmental factors affecting microbial activity when using different types of microorganisms, but it is difficult for geotechnical engineers to have enough professional microbial knowledge, so there are still many problems in practical application.

4.3. Effects of concrete properties on microbial remediation

Four properties of concrete are particularly important for microbial activity and SH effects: permeability, porosity, crack size, and aging rate. Pores in concrete represent interconnecting voids of a certain size in which soluble components can spread and in which microorganisms are therefore distributed[9]. If porosity and permeability are related, porous concrete can have higher permeability and greater opportunities for microbial activity, but small or disconnected pores will also reduce permeability and reduce the opportunity for microbial activity, and the microbial repair effect will be affected. Cracks in concrete not only affect its life span, but also greatly affect the activity of microorganisms. Fractures can store water and activate microorganisms, which play an important role in the SH effect. In addition to water, cracks can be filled with different fluid phases, such as air, salt, and acid solutions[11]. The crack size will limit the efficiency of SH effect. If the crack width is very large, SH effect will not be able to develop in the whole crack because there are not enough microorganisms to induce enough $CaCO_3$. However, in a narrow crack, the same number of microorganisms is sufficient to meet the required SH effect. However, due to the small crack size, the transportation of microorganisms will be impeded, resulting in too few microorganisms in the crack, which will also affect the SH effect.

Concrete aging is an inevitable process, usually appear in the individual components of the structure, is to lead to the concrete components uneven and crack phenomenon. Fracture monitoring results obtained from a set of scientific studies show that the SH effect is better during the first 28 days, after which the fracture filling rate slows down[12]. In a recent investigation of crack healing ability of concrete materials, Justo Reinoso et al.[12] demonstrated the repeatability of SH effect after 22 months in the same concrete sample, at the same location of the previous crack. This indicates that due to the decrease in the number of microorganisms after the initial SH effect, the number of microorganisms cannot support the occurrence of SH effect for a period of time. However, the concrete matrix contains active microorganisms in different locations, and the new cracks heal with an average healing rate of 93.3% through the transport of pores and cracks.

Since the characteristics of concrete are usually a function of a large number of different influencing factors, such as the characteristics of applied components, the mass ratio of components and many technical factors[11], the biggest problem in the research process of microbial concrete may be the monitoring under actual conditions. Unlike most laboratory conditions where parameters can be controlled, the monitoring of microbial concrete requires multiple variables in the field process from pre-use to post-repair, but until today there has been a lack of standardized monitoring methods.

5. Conclusion

Since the use of concrete repair microbes undoubtedly represents the sustainable innovation and the frontier problem of cement base material industry, from the engineering application, environment protection and economic save three ways, microbial performance of concrete material are very good, for repairing materials and surface treatment, since the crack repair provides a new choice, and have potential applications in roads, tunnels, and large infrastructure, etc., To improve its durability and mechanical properties. Cement-based composites supported by microbial technology can reduce maintenance costs, effectively extend the life of the structure and minimize environmental problems.

Although the application of microorganism in concrete self-healing technology has a good application prospect and promotion prospect, the wide application of this technology is limited by several problems. To alleviate these problems, we need to address the following tasks: first, reduce the cost of technology. Currently, the relatively high cost of MICP technology prevents its large-scale application. Second, interdisciplinary cooperation should be strengthened in the future, which needs the strong support of bioprocess professionals. Third, develop a set of standardized monitoring methods, so that uniform treatment and monitoring process can be obtained under practical conditions.

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