Research and Application of Microbial Cement in Civil Engineering

Xinyi Tang, Longxiang Chen, Guangtao Zhang, Ping Jiang*

School of civil engineering, Shaoxing University, Shaoxing, 312000, China
* Corresponding author: Ping Jiang

Abstract: A large number of scientific studies have found that the process of consolidation diagenesis is not only a simple chemical action, but also a series of biological sedimentation. Based on this discovery, scientists have conducted in-depth research on the cementation and mineralization mechanism of Microbial Induced Calcite Precipitationground (MICP), and studied and prepared microbial cement in line with engineering practical application by exerting man-made environmental influence. It is used to deal with a series of complex problems such as building concrete cracks, foundation solidification soil, engineering energy conservation and carbon reduction. By consulting domestic research reports, this paper summarizes its research development and practical application, and reviews the existing research and application fields, in order to look forward to the future research and development direction.

Keywords: microbial cement; microbial induced calcite precipitationground (MICP); crack repair; solidified soil

1. Introduction

In order to meet the needs of infrastructure development in China, a large number of Portland cement as a gel material in the preparation and application of concrete plays a key role in the vigorous development of civil engineering worldwide. Many scholars and research institutes have also done a lot of research on the material compatibility and strength enhancement of Portland cement. However, as the impact of the greenhouse effect has attracted more and more attention, the concept of green, low-carbon and environmental protection has been deeply rooted in the hearts of the people. It is found that the Portland cement we are using has serious problems such as high energy consumption and environmental pollution. Therefore, it is urgent to find a new type of gel material with low carbon, energy saving, green healthy and durability to replace it. Microbial cement is produced in this context.

It is found that microorganisms have widely existed in nature since the formation of the earth. After thousands of years of mineralization and consolidation in the complex natural environment, they participate in and create the complex and diverse natural landforms. Microorganisms can mineralize through their own biochemical reaction to form natural mineral materials with orderly arrangement, excellent structure and good cementitious properties. Its excellent characteristics can replace the Portland cement widely used at present, and widely meet the practical engineering needs of particle solidification, crack repair, component preparation, heavy metal ion solidification and so on. Microbial cement is a new kind of gel material which uses calcite induced by microorganism as cement material to connect loose particles to become a whole and obtain certain mechanical properties [1].

2. Rresearch Status of Microbial Cement

2.1. Foreign Research Status

In a study published in Nature in 1973 by Boquet E, it was found that some microorganisms [2] were found in natural soil to produce calcium carbonate crystals in soil, which resulted in soil solidification and hardening. This report prompted later scholars to study the microbial biological mechanism, and laid a solid foundation for the discovery and research of microbial cement.

The earliest research on microbial cement is known to have started with the doctoral research project "Microbial $CaCO_3$ Precipitation for the Production of Biocement" [3] by Whiffin, VS. (2004) of Murdoch University, Australia. In the next study, Dr. Whiffin used the microbial reagents to treat a 5-meter sand column, and observed and measured the mechanical properties of the column. The results showed that the strength and rigidity of the sand column were significantly increased several times. The viewpoint that microbial carbonate precipitation can be used to improve the bearing capacity of soil is proposed, and this method is obviously better than the widely used soil treatment method [4]. In this context, microbial cement materials have entered the researchers' field of vision, and the technology of microbial induced calcite precipitationground (MICP) has emerged and developed.

Subsequently, Bosak T, Newman DK et al. conducted a further study on the cementation mechanism and influencing factors of microbial-induced calcium carbonate precipitation, and the experimental results showed that the concentration of microorganisms was an important factor leading to the amount of calcium carbonateprecipitation. When the calcite content is low and the microbial concentration isover-saturated, the calcite surface can be stimulated to produce more calcium carbonate precipitation and promote its growth and repair [5].

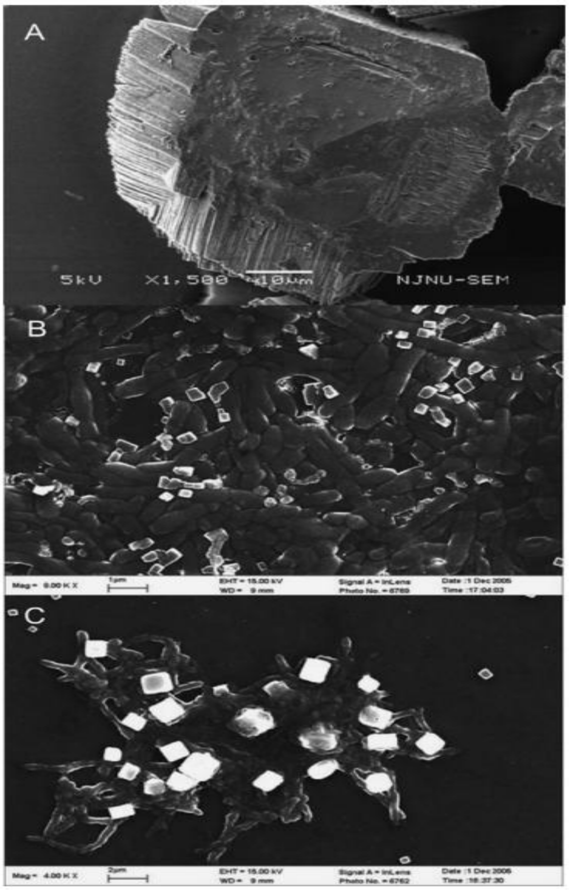

Figure 1. SEM scanning image of calcite [4]

Lian B et al. studied the mechanism of microbial-induced calcite mineralization, and proposed the mechanism of B. megaterium mediated calcite mineralization by measuring carbon isotopes in the nucleus. We suggest that the whole process of calcium carbonate precipitation is involved in extracellular surface and intercellular growth in the local microenvironment, and hypothesize that the formation of calcium carbonate precipitation may be controlled by cellular biological activities during bacterial respiration. At the same time,the author observed the formation of calcite on the outer surface of the cell by SEM scanning [6], as shown in Figure 1.

In subsequent studies, the researchers further measured and enhanced the physical properties of the microbial cement by adding different amounts of calcite and fiber. Yang X, Ph.D. et al studied the strength characteristics of basalt fiber reinforced biological cement (BFRB) sand samples with different calcite content and fiber content, and introduced reverse injection to improve the uniformity of calcium carbonate in the component. The volume content of calcite induced by microorganisms was determined by the final formula derivation Civ [7].

$$C_{iv}=\frac{100V_{ca}}{V_t}=\frac{\frac{100m_sC_{ca}}{100G_{ca}\rho_w}}{m_s\left(1+\frac{C_{bf}}{100}\right)\rho_d}=\frac{\frac{\rho_d}{\rho_w}}{1+\frac{C_{bf}}{100}}\cdot\frac{C_{ca}}{G_{ca}} \quad (1)$$

The experimental results show that, due to the interlocking, strengthening and binding effects within the structure, the unconfined compressive strength (UCS) and split tensile strength (STS) of the members increase significantly with the increase of calcite or basalt fiber content [7]， as shown in Figure 2.

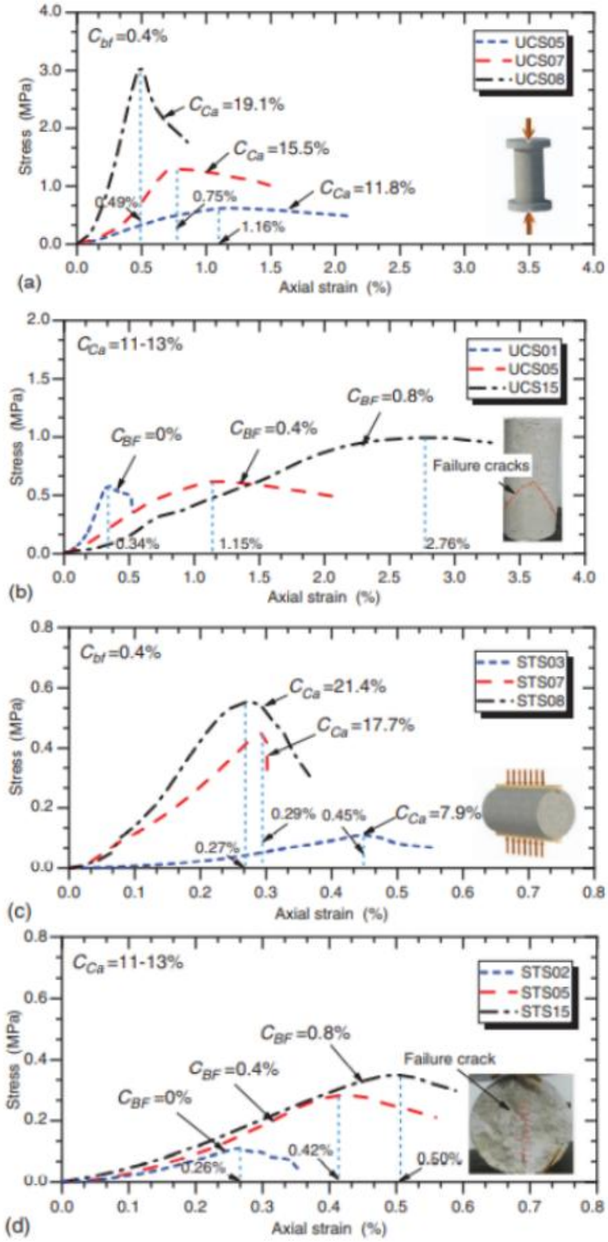

Figure 2. Typical stress-strain curves of unconfined compressive strength test under different conditions: (a) calcite content;(b) Fiber content (the illustration shows the failure crack);And the typical stress-strain curves of different splitting tensile strength tests are as follows: (c) calcite content;(d) Fiber content (failure crack shown in illustration)

2.2. Domestic Research Status

The team led by Professor Qian C from the School of Materials Science and Engineering of Southeast University has been studying this topic since 2004, which is the earliest known team in China. The team led by Professor Qian C compressed the long process of microbial cementation in nature into a few days through artificial control, conducted biological research on the cementation mechanism and mineralization mechanism of microbial cement, prepared microbial cement with good performance, and popularized it into practical engineering projects. Wang R, Qian C [8] and others cultivate calcium carbonate precipitation in a short time by cultivating breeding bacteria, adding appropriate calcium ions and applying biochemical action of bacteria. The study further reveals the mechanism of microbialdeposition of calcium carbonate and the influencing factors of temperature on the shape of calcium carbonate particles, and gives researchers a new idea of preparation ofcalcium carbonate. The equation obtained is as follows:

$$Bacterial\ strainA + Nutrient\ sourceB \longrightarrow CO_3^{2-}\ （Enzymolysis） \tag{2}$$

$$Cell + Ca^{2+} = Cell - Ca^{2+} \tag{3}$$

$$Cell - Ca^{2+} + CO_3^{2-} = Cell - CaCO_3 \tag{4}$$

Subsequently, the researchers searched for the factors affecting the formation rate of calcium carbonate through experiments in order to further improve the reaction rate of microbial cement. The deposition rate of calcium carbonate was studied by the researchers of Zhu W [9], Huang Y [10], Qian C [11], respectively, on the factors of the concentration of biological medium, the number of bacteria, the reaction precipitation time, the ambient temperature, the substrate concentration and the nucleating agent $MgS0_4$. The experimental results show that the factors affecting the deposition rate and amount ofcalcium carbonate are as follows:

$$Substrate\ concentration > medium\ concentration > inoculation\ amount > nucleating\ agent$$

MICP mineralization mechanism mainly includes biological control andbiological induction. Biological induction is a biological mineralization process induced by changes in physical and chemical conditions caused by a series of effects of microbial physiological activities on the surrounding solution environment [12]. According to the results of previous studies, Sun D and Xu W et al. [13] have found that the carbonate biomineralization is mainly induced by aerobic microorganism [14], sulfate reducing prototype microorganism [15], urea hydrolyzed microorganism [16].

In the medium of nutrient deficiency, it was found that aerobic microorganism could grow well. Sulfate reducing prototypes microorganisms are not used in concrete structures because of their decomposition and destruction. Urea hydrolyzed microorganisms are easy to cultivate in laboratory and nature, and they are widely existing in our lives. Researchers found that the induced calcium carbonate deposition process has the advantages of easy reaction control, convenient operation and high mineralization efficiency. Therefore, it has been widely used in practical engineering construction [17].

Wang L, Wang X and Cui M, et al. further studied urease, carbonic anhydrase gene and protein structure in microbial cement based on the existing research, and the results showed that their biological structure played a certain synergistic role in the formation of calcium carbonate precipitation, and the reaction rate can be accelerated by changing the biological structure of microorganisms [18]. This discovery further expands the research direction of researchers on microbial cement. The assembly process of microbial urease and the simulation diagram of urea metabolism are shown in Figure 3.

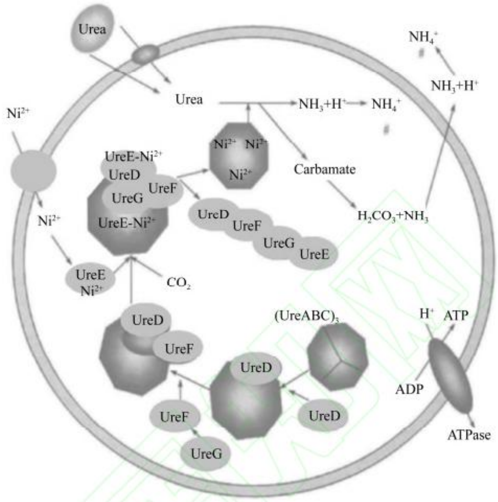

Figure 3. Assembly process of microbial urease and simulation diagram of urea metabolism [19]

3. Application Status of Microbial Cement

Microbial cement has many advantages over traditional Portland cement. On the one hand, the production and preparation of microbial cement consumes less energy and effectively reduces greenhouse gas emissions. At the same time, microbial cement can be prepared normally at the temperature of about 30 degrees centigrade, while the preparation temperature of traditional cement is 100 times that of biological cement. On the other hand, the particle size of biological cement is smaller, and it is easier to fill the smaller aggregate or concrete gap evenly. And its viscosity is lower, it is easier to penetrate into the deeper members, and finally the strength and uniformity of the members are significantly enhanced. Based on these advantages, microbial cement can be applied in crack repair, foundation reinforcement and consolidation of soil heavy metals in practical engineering.

3.1. Concrete Crack Repair

As a brittle material, concrete is easy to produce shrinkage cracks, temperature cracks, uneven settlement cracks and so on due to the external environment or its own chemical reaction in practical engineering components. These cracks will lead to leakage of concrete components, which will be exposed to air, resulting in chemical reaction between concrete and reinforcement, resulting in corrosion and other hazards. It will directly affect the structural stability and strength of concrete buildings for a long time.

Biological cement is the best way to repair concrete cracks at present. By injecting corresponding microorganisms into the fracture, the mineralization of microbial metabolism is used to induce calcium carbonate precipitation, and then the fracture is repaired, which is the so-called microbial induced calcite precipitationground (MICP). The main mechanism of MICP is that microorganisms decompose urea to produce carbonate ions, which combine with calcium ions to form inorganic minerals [20]. Figure 4 is the schematic diagram of calcite crystal filled sandstone produced by MICP process.

$$CO(NH_2)_2 + 2H_2O \longrightarrow 2NH_4^+ + CO_3^{2-} \quad (5)$$

$$Ca^{2+} + CO_3^{2+} \longrightarrow CaCO_3 \downarrow \quad (6)$$

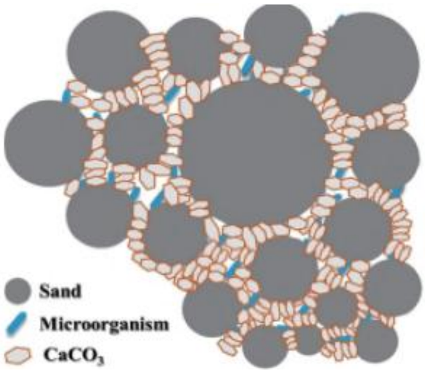

Figure 4. Schematic diagram of calcite crystal filled sandstone produced by MICP process

Compared with other concrete crack repair technologies, microbial repair has simpler actual operation, faster repair speed, and can automatically repair the cracks that cannot be detected inside [21]. But the results show that when the depth of fracture is deep, the effect of the inner layer restoration is not ideal, which is closely related to the injection mode, internal environment and concentration of microorganisms. Figure 5 shows the self-healing model of microorganisms.

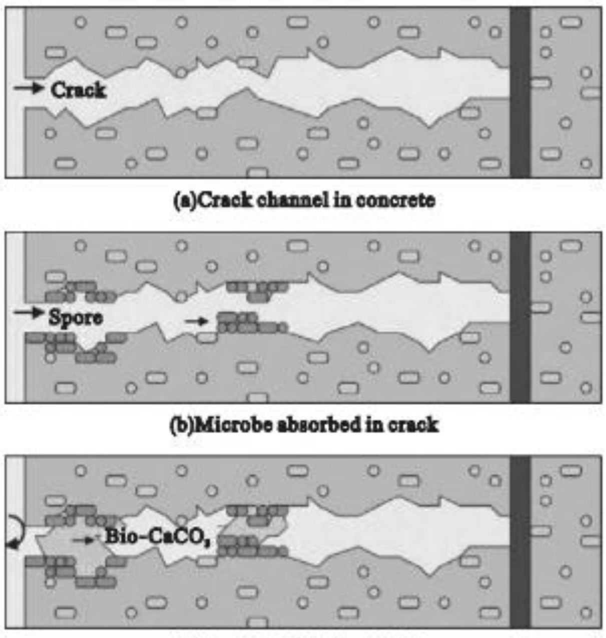

Figure 5. Self repairing model of microorganisms

3.2. Consolidation of Loose Foundation

In the actual project, in order to meet the seismic requirements of the loose foundation structure in coastal cities, a lot of manpower and material force is often needed to strengthen the foundation. The common methods of foundation reinforcement include tamping and cement pile, but these methods will have a certain impact on local environment and resources. In recent years, a large number of researches have shown that microbial cement has a significant effect on the foundation reinforcement. Hui Rong et al. [22] found that the $MgCl_2$ concentration in the process of microbial induced calcium carbonate deposition would affect the performance of the consolidated sand column. When the $MgCl_2$ concentration was 2.5mol/L, the porosity and compressive strength of the sand column were the lowest and the highest. By adding the corresponding microbial cement to the soil to be treated, the soil can be solidified and hardened, and the bearing capacity of the soil can be greatly improved. But the environment conditions needed for microbial growth are still strict at present, which is not conducive to the application in the actual construction process.

3.3. Heavy Metals in Consolidated Soil

Due to the rapid development of urbanization and the expansion of industrialization scale, a large number of heavy metals are discharged into the soil through air and water sources, which leads to the destruction of land and grain production, the remarkable reduction of crop yield and quality, and the impact on the healthy and sustainable development of national economy. In order to eliminate the heavy metal pollution in soil, bioremediation technology emerged. Bioremediation technology is to use the natural mineral resources in soil, and introduce strain a by adding substrate bio cement, so that microorganisms in soil absorb heavy metals and mineralize and precipitate in it. The removal rate can reach 50% - 70%, and the environmental protection can be promoted[23]. The biological reaction process is as follows.

$$Bacterial\ strainA + Nutrient\ sourceB \longrightarrow CO_3^{2-}\ (Enzymolysis) \quad (7)$$

$$Cell + Heavy\ metal\ ion = Cell - Heavy\ metal\ ion \quad (8)$$

$$Cell - Heavy\ metal\ ion + CO_3^{2-} = Cell - Heavy\ metal\ carbonate \quad (9)$$

$$Substance\ matter(SM) + Heavy\ metal\ ion = Substance\ matter(SM) - Heavy\ metal\ ion \quad (10)$$

$$SM - Heavy\ metal + CO_3^{2-} = SM - Heavy\ metal\ carbonate \quad (11)$$

4. Existing Problems and Development Prospects

4.1. Existing Problems

Microbial cement MICP technology has a wide application prospect, but microbial cement as a new technology, which involves the cross integration of many disciplines such as engineering and biology, and the research difficulty is self-evident. There are still some problems in the application of microbial cement from laboratory to large-scale practical application. Firstly, although the reaction rate has been greatly improved under the research of Professor Qian, compared with traditional minerals such as silicate, the mineralization rate of micro cement and biological cement is low, which can not well meet the needs of practical engineering. Secondly, the mechanical properties such as strength and hardness of components prepared by microbial cement can not meet high requirements, and they need to be strengthened by adding appropriate fiber materials[24]. However, which kind of fiber material is the most economical and reasonable needs our further research.

Finally, the microorganisms contained in biological cement can survive for up to 6 months, and the survival time is short. Because the characteristics of each strain with MICP function are different, there are also great differences in the adaptability to the application environment. At present, various application studies using MICP are basically carried out in the laboratory simulation environment. The lack of ideal natural strains can not meet the complex and changeable natural environment.

4.2. Future Outlook

Microbial cement needs a long way to be applied in civil engineering construction on a large scale. At this stage, our researchers need to strengthen the research on microbial cement and carry out interdisciplinary exchanges and cooperation. At the same time, the society should formulate relevant industry standards to promote the development of biological cement industry. Biological cement is a living material. When there is damage inside the concrete component, the microorganisms in it can restart the micp program to repair the building by themselves [25]. Realizing the so-called microbial intelligent concrete is roughly similar to the intelligent construction concept implemented at this stage. It will be a subversive material and will promote the reform of the industry. It can be predicted that in the near future, microbial concrete will be widely used in all aspects of our life. Its application will play an important role in promoting energy conservation and emission reduction, alleviating the greenhouse effect and implementing the green concept.

5. Summary

As a new building material, biological cement has been studied by researchers at home and abroad on its mineralization, cementation mechanism, influencing factors and the enhancement of mechanical properties of biological cement concrete. The research results show that it has a wide application prospect, which can be used for cemented sand column, self repair of concrete cracks, solidification of soil, treatment of heavy metal soil, absorption of CO_2 in the environment and so on. Building materials will play an important role in the next generation of sustainable development. However, microbial cement has no detailed practical guidance and operation process for specific practical application, and its applicability and operability are not strong. Therefore, it is necessary to strengthen the management and further study the practical operation process of biological cement. Considering the harsh conditions of microbial cement, in the subsequent research and design, we will formulate a standard process that conforms to the characteristics of microbial cement for a practical engineering application.

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