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Research Progress of Slope Stability based on Microbial Reinforcement

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Abstract

Microbial-induced calcium carbonate deposition (MICP), as a new slope reinforcement technology. The mechanism of this technology is to use the metabolic activity of microorganisms to generate CaCO3 precipitation, which can change the physical and chemical properties of sole. This article systematically summarizes the impact of five key factors on the reinforcement effect to slope and draws the following conclusions. The difference in soil slope environment will produce different reinforcement effects; The activity of microorganisms is higher in the range of 3~45°C; The PH value in the range of 8~9 is conducive to the formation of calcium carbonate; The grouting method mainly affects the distribution of calcium carbonate in the soil slope; With the increase of bacterial solution concentration, the bacterial activity is increased, soil slope reinforcement effect is better.

Keywords

Microorganisms; Reinforcement Mechanism of Soil Slope; Factors Affecting Solidification; Slope Stability; Ambient Temperature.

1. Introduction

Geotechnical engineering mainly involves the use, remediation and transformation of rock and soil slope. The soil slope reinforcement technology has played an important role in geotechnical engineering. The traditional method of foundation treatment mostly use precompression consolidation or chemical grouting to strengthen the soil slope. Precompression consolidation requires the use of large machinery, which is more suitable for large-scale soil slope reinforcement. It has the characteristics of long construction period, high cost and significant influence on soil slope structure. The chemical grouting needs to pump chemical materials into the soil slope layer or cracks, and most of the chemical materials used are harmful, which will cause harm to the environment. This is contrary to the concept of building a resource-saving and environment-friendly society advocated in recent years.

Microbial-induced calcium carbonate deposition (MICP), as a new type of green and environmentally friendly soil slope reinforcement technology. Due to its high technical value, it has attracted the attention of scholars both at home and abroad. The principle of its action is to use the ability of microbial mineralization to produce calcium carbonate to cement the soil slope and achieve soil slope reinforcement. Under the research of more than ten years, this technology has been preliminarily applied in various fields. At present, the results of this technology in the study of soil slope microbial reinforcement are relatively less. Due to the lack of construction technology and related knowledge, the research is still in the laboratory stage, and relatively few cases are applied to practical projects. Chang Daoqin[1] et al. used the ability of microorganisms to solidify soil slope to solve the problem of heavy metal pollution of copper tailings in arid and semi-arid areas, which has application value of repairing and improving polluted soil slope quality. Yue Jianwei[2] et al. explored the optimal

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concentration of glutinous rice pulp to strengthen silty soil slope in the middle and lower reaches of the Yellow River to improve its strength and stability. Yu Chengcheng[3] et al. provided reference for the practical application of microbial geotechnical technology to solve the expansion and contraction of expansive soil slope. Yang Zuan[4] et al. applied this technology to the actual project of strengthening and repairing the empty drum on the exterior wall of Makikang in Potala Palace.

This article summarizes the research results in recent years, the mechanism of microbial action and the factors affecting the soil slope reinforcement effect are summarized. The mechanism of reinforcement is to use the metabolic activity of microorganisms to generate calcium carbonate with cementation effects to change the physical and chemical properties of the soil slope mass. The factors that affect soil slope reinforcement include soil slope environment, temperature, PH value, grouting method and material concentration, and so on. In addition, some scholars have enhanced the mechanical properties of loess through enzymatic carbonate deposition technology.[21-22].

2. Curing Mechanism of Microorganism

There are mainly four ways of microbial reaction, including urea hydrolysis, denitrification, trivalent iron reduction and sulfate reduction[5-6]. Among them, the urea hydrolysis reaction principle is relatively simpler than other methods. The test process is easy to operate, the reaction degree is easy to control, and it can deposit a large amount of calcite in a short period of time. So the microbial urea hydrolysis method is widely used in MICP technology research. Most of the studies on MICP grouting are based on pasteurii, a high-yielding urease-producing basophilic bacterium that can promote urea hydrolysis. It can adapt to the environment well, and produce urease that can accelerate the generation of CO_3^{2-} and NH^{4+} in the metabolic process, which is widely distributed in the soil slope[7-8]. The first step of urea hydrolysis reaction is urea hydrolysis. Firstly, urea is hydrolyzed to produce ammonia and carbon dioxide under the catalytic action of urease produced by microorganisms. Secondly, ammonium ions and bicarbonate ions are generated in an alkaline solution environment.In an alkaline environment, bacteria with sufficient nutrient solution transform carbon source and nitrogen source in the nutrient solution into carbon dioxid e and ammonia by means of metabolic action. The chemical reaction equation is shown in Equation (1).

$$CO\left(NH_2\right)_2 + 3H_2O \xrightarrow{DUrease \quad catalysis} 2NH_4^+ + HCO_3^- + OH^- \tag{1}$$

By changing the microstructure of calcite morphology to improve the macro performance of soil slope, so the morphology of calcite can be changed to meet the needs of different engineering construction Bacillus pasteurii takes urea as energy, and with the increase of solution PH value, CO_3^{2-} content also gradually increases.

The second step is biochemical reaction. The positively charged calcium ions are adsorbed on the negatively charged bacterial cells, acting as the crystal nucleus to combine with carbonate ions to generate calcite (calcium carbonate with cementing effect). The chemical reaction equations are shown in Equation (2) and Equation (3). The urea hydrolysis process of urease-producing bacteria is shown in Fig. 1.

$$Ca^{2+} + Cell \xrightarrow{Adsorption} Cell - Ca^{2+} \tag{2}$$

$$CO_3^{2-} + Cell - Ca^{2+} \rightarrow Cell - CaCO_3 \downarrow \tag{3}$$

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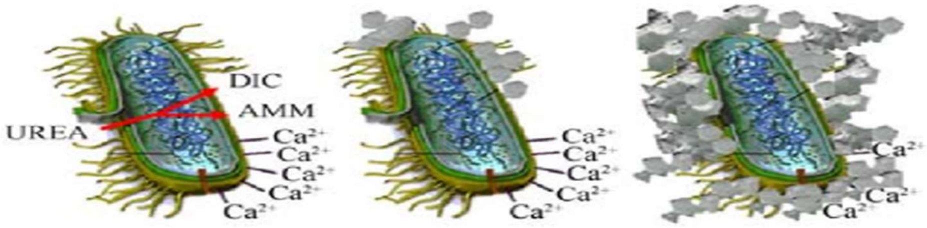

(a) Urea decomposition (b) Ca_2^+ adsorption (c) $CaCO_3$ sedimentation

Fig. 1 Schematic diagram of urea hydrolysis by urease-producing bacteria[8]

Bacillus pasteurii is suitable for alkaline environment, it not only produces urease for urea hydrolysis, but also provides nucleation point for calcium carbonate deposition. Its working principle mainly using the bacteria to grow and reproduce in porous media, and react with the substances in the nutrient solution to generate calcite. The shape and size of calcite are affected by many aspects, resulting in different structural appearances. Such as parallelepiped, thin sheet or sword-shaped, spherical particles, etc. The generated calcite can fill the pores of soil and improve the mechanical properties of soil slopes by changing the microstructure of the soil.

3. Factors Affecting the Curing Effect

The process of microbial solidification of soil slope includes a series of complex biological reactions and chemical reactions. Therefore, the effect of microbial solidification is not only affected by a certain factor, but also the result of multiple factors. At present, in a large number of laboratory tests conducted by domestic and foreign scholars, it has been found that the main factors affecting the solidification effect are soil slope environment, temperature, pH value, grouting method, material concentration and other factors.

3.1 Soil Slope Environment

Soil slope environment can affect the effect of microbial curing. According to the research results in recent years, it has been found that coral sand, weathered red sandstone soil slope, marine sand and other soil slopes have been used for research. Lin Wei[9] applied MICP technology to the reinforcement of sea sand to explore the feasibility of microbial reinforcement technology to reinforce sea sand. Van paassen[10] et al. used MICP technology to reinforce gravel layer and found that this technology can effectively improve the strength of gravel layer. The differences in soil slope environment include the internal substance of soil slope, particle gradation, relative density of soil slope, moisture content, etc, which mainly affect the deposition rate of calcium carbonate. Ma Qiang[11] studied in detail the effects of particle gradation, relative density, average particle gradation and other factors on microbial transport. Among these differences, the effect of particle gradation on MICP is the most obvious. GOWTHAMAN S[12] et al. explored the effects of different particle gradation on the production and distribution uniformity of calcium carbonate. So it was found that the calcium carbonate precipitation rate in fine sand is higher than that in coarse sand, and the closer to the pouring source the higher the content of calcium carbonate. Both too large and too small soil slope particle sizes are not conducive to MICP reinforcement, and the strength and calcium carbonate content are the highest when the particle size is within the range of 0.3~0.6 mm[13].

3.2 Temperature

Temperature affects the activity of microorganisms to a large extent. The activity of microorganisms will be inhibited at low temperature, and the microorganisms will die at high temperature. Krieg[14] et al. found that microorganisms can perform microbial solidification in the range of 3~45°C. Peng Jie[5] et al. used Bacillus pasteurii to conduct experiments at temperatures of 10°C, 14°C, 18°C, 21°C and 25°C, respectively. The results showed that the higher the temperature, the faster the rate of calcium carbonate precipitation and the more calcium carbonate was generated. Huang Yan[15] et al.

used Bacillus pasteurii to conduct experiments at different temperatures, and found that the bacterial reproduction speed was the fastest at 30°C, while calcium carbonate precipitation was almost not detected at low temperature of 10°C. It can be seen that temperature affects the effect of microbial solidification of soil slope by affecting the rate of calcium carbonate formation and microbial activity.

3.3 PH Value

PH value is one of the important factors affecting MICP reaction. The alkaline environment is beneficial to the growth and reproduction of most microorganisms, but the PH value too high will affect the reproduction of microorganisms or even direct death. As for the optimal reproductive environment of microorganisms, most microorganisms exist in the environment with a PH value of 5~9, but the optimal growth environment of different varieties of microorganisms has different PH values. Cui Rui[16] found through experiments that the content of calcium carbonate generated was higher when the PH value was in the range of 8~9. Zhang Haili[17] et al. used Bacillus pasteurii to measure the bacterial growth and urease activity at the four gradients of PH values of 7, 8, 9 and 10. The results showed that the growth of bacteria was promoted when the pH value was 8, and the concentration of bacteria and urease activity reached the maximum after 48h of culture. When the pH value was 10, the growth of bacteria was inhibited by the over alkaline environment.

3.4 Grouting Method

In practical application, MICP technology is usually to inject bacteria into the soil slope that needs to be strengthened, inducing calcium carbonate precipitation to cement the soil slope, to achieve the purpose of solidification. The grouting method has an important influence on the uniformity of calcium carbonate and deposition amount and distribution, which will directly affect the reinforcement effect, as shown in Table 1.

Table 1. Experimental study on grouting method for soil slope reinforcement

Grouting method	Experimental description	Main conclusion
Indirect grouting method	Liquefiable sand; The bacterial and cementing fluids were injected separately	The uniformity of liquefiable sand reinforcement can be ensured as much as possible[18]
Step grouting method	Masonry; Infusion of bacterial liquid three times	Standing for a long enough time can allow the cementing fluid to fully react with the bacterial fluid[4]
Surface spraying two-phase method	Beach sand;The surface spraying method is combined with the surface spraying injection method	Using surface spraying two-phase method can get better reinforcement effect[19]

The existing grouting methods are mainly include gravity infiltration grouting and surface spraying. The strength of the samples formed by infiltration grouting is high, but its ductility is poor. The reinforcement method of surface spraying makes it difficult for the bacterial solution to penetrate into the clay, and the distribution of calcium carbonate is uneven[20]. The most direct reason for the uneven distribution of calcium carbonate is the uneven distribution of calcium ions. The content of calcium ions can be used as an indicator to monitor the production of calcium carbonate precipitation.

3.5 Material Concentration

The concentration of bacterial solution, nutrient solution and cementing solution are all material concentration. The cementing solution required by microorganisms can only have a good promoting effect on the growth of microorganisms when the concentration is appropriate. The concentration of bacteria will affect the shape and size of calcium carbonate crystals, thus affecting the properties of soil slope. Larger calcium carbonate crystals can bond well with coarse-grained soil slope, resulting in higher interparticle bond strength and improved mechanical properties. Smaller calcium carbonate crystals play a cementing role in fine-grained soil slope, improving soil slope permeability. The microbial cementing solution mainly provides nutrients, calcium sources and nitrogen sources.

From the above research results, it can be seen that the material concentration has an important impact on the modification of MICP. The soil slope performance improved by bacterial solution and cementing solution with different compositions and concentrations is different, and its application fields in practical engineering are also different.

4. Conclusion

(1) The mechanism of action of MICP is to use the metabolites of specific microorganisms to induce the formation of calcium carbonate crystals that can cement and fill the soil slope. This technology can cement the loose soil slope particles into a whole, playing the role of solidifying soil slope. The most widely used is the microbial based on urea hydrolysis reaction. Microorganisms will degrade and produce CO_3^{2-} and NH_4^+. After chemical reaction, CO_3^{2-} combines with bacterial cells to form calcium carbonate crystals. It can be used to reinforce soil slope, seepage control, and reinforce liquefied foundation, etc. It has good applicability in a variety of soil slope environments.

(2) MICP technology is affected by many factors in the application. This paper systematically summarizes the influence of key factors such as soil slope environment, temperature, PH value, grouting method and material concentration on the reinforcement effect of soil slope, and mainly draws the following conclusions. The difference in soil slope environment will produce different reinforcement effects. The activity of microorganisms is higher in the range of 3~45°C. The PH value in the range of 8~9 is conducive to the formation of calcium carbonate. The grouting method mainly affects the distribution of calcium carbonate in the soil slope. With the increase of bacterial solution concentration, the bacterial activity is increased. According to the actual engineering needs, choose the appropriate concentration of bacterial solution and cementation solution.

(3) At present, Microbial reinforcement has enormous development potential to soil slopes. The reinforcement effect is influenced by some factors, such as temperature, pH value, etc. In the future, more MICP models will be established for further research.

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