Review on Research Progress of MICP Technology

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Abstract. MICP technology is a new technology proposed for soil reinforcement research in recent years, which has the advantages of environmental protection and sustainability. Through the review and analysis of domestic and foreign literature, the mechanism of microbial mineralization reaction and the research progress of domestic and foreign scholars were comprehensively summarized. This paper introduces the basic principle of urea hydrolysis in MICP technology, and expounds the control factors of microbial mineralization experiment and the practical application of this technology in engineering. Finally, the future development prospect of MICP technology is forecasted.

1. Introduction
Soil is the product of rock weathering, which has the physical characteristics of dispersity, multiphase and natural variability, so its mechanical properties are poor and need to be improved. The traditional methods to deal with the soil with poor mechanical properties are mainly soil replacement and compaction and cement or chemical material grouting reinforcement [1-2]. Microbial induced calcium carbonate precipitation technology has been developed for more than ten years, and it can be described as a new soil improvement and reinforcement technology [3-4]. Due to its advantages of environmental protection, economy, high efficiency and controllability, it has attracted extensive attention of scholars at home and abroad, and has been applied to various fields of engineering, such as foundation reinforcement, slope anti-seepage, crack repair and contaminated soil treatment.

2. Basic Principles of MICP Technology
Microbial Induced Calcium Carbonate Precipitation (MICP) is a biomineralization reaction widely existing in nature, and urea hydrolysis MICP is the simplest, best controlled and most common one. Its basic principle is that urease is produced by Bacillus pasteurii and other bacteria to catalyze the hydrolysis of urea into ammonia and carbon dioxide, and then ammonia is further hydrolyzed into ammonium ion and hydroxyl ion, and Carbon dioxide is converted into bicarbonate ions in alkaline environment. Finally, bicarbonate ions are combined with calcium ions in cementation solution to form calcium carbonate precipitation in alkaline environment. The specific chemical reaction formulas are follows [5].

\[
\text{CO(NH}_2\text{)}_2 + \text{H}_2\text{O} \rightarrow 2\text{NH}_3 + \text{CO}_2
\]  

(1)
\[
\begin{align*}
\text{NH}_3 + \text{H}_2\text{O} & \rightarrow \text{NH}_4^+ + \text{OH}^- \\
\text{CO}_2 + \text{OH}^- & \rightarrow \text{HCO}_3^- \\
\text{HCO}_3^- + \text{Ca}^{2+} + \text{OH}^- & \rightarrow \text{CaCO}_3 + \text{H}_2\text{O}
\end{align*}
\]

3. Experimental Research on MICP Technology

Recent studies have shown that the reaction environment, geometric size, particle size, curing method and chemical treatment method will affect the effect of microbial mineralization experiment.

3.1. Reaction Environment

The bacterial concentration, urea concentration, calcium ion concentration, temperature and pH will all affect bacterial urease activity and calcium carbonate production, thereby affecting the solidification effect of sand [6-8]. Bacterial urease activity and calcium carbonate production are positively correlated with bacterial solution concentration, and when bacterial solution concentration is 5~10, the strength of sandy soil is higher and the permeability coefficient is smaller, the higher the bacterial solution concentration, the more nucleation sites are provided and the more calcium carbonate production [9-10]. With the increase of urea concentration, bacterial urease activity first increases and then decreases, and there is an optimal value. Zhao [11] obtained through experimental research that the optimal value of urea concentration is 1.6mol/L. Jia et al. [12] found that urea concentration greater than 5mol/L will inhibit bacterial growth and reproduction, reduce bacterial urease activity, and lead to the decline of calcium carbonate production. High concentration calcium ion solution has obvious inhibitory effect on bacterial urease activity, which decreases greatly, and also affects the precipitation efficiency of calcium carbonate [11,13]. Peng et al. [14] and nemati et al. [15] found that with the increase of temperature, bacterial urease activity increased, calcium carbonate production increased, and the production rate increased. Bacterial urease activity is higher in alkaline environment, which is more suitable for microbial mineralization reaction. Zhang [16] found that when the pH increases from 7.0 to 9.0, the production of calcium carbonate nearly doubles. During the reaction process, ammonia is hydrolyzed to obtain hydroxide ions, which increases the pH value of the reaction solution, and promotes the conversion of bicarbonate ions into carbonate ions, thereby promoting the formation of calcium carbonate precipitation [17-18].

3.2. Geometric Size

The size is mainly for reaction vessel, sand column and calcium carbonate crystal. Wen et al. [19] found that the large-scale model tank can provide more penetration paths for bacterial fluid and cementation fluid, which make it fully react with sand, and generate more calcium carbonate, so it has higher unconfined compressive strength. The size of calcium carbonate crystals generated in the curing test is different, under the premise of relatively uniform crystal distribution, large-sized grains can more effectively fill the pores in the sand column, and the structure is more stable and dense, and the compressive strength of sand is higher [20]. Shen [21] found that a single grouting is not enough to bond the sand column for grouting reinforcement of small size sand column, and multiple grouting is necessary to bond the sand column as a whole, for grouting reinforcement of large size sand column, it is necessary to inject bacterial solution with low concentration and temperature in stages to reduce the generation of calcium carbonate in the grouting process and prevent the occurrence of microbial flocculation.

3.3. Particle Size

Many studies have shown that the particle size of sand greatly affects the strength of solidified sand. The sand with small particle size has small interparticle pores, which is easier to fill calcium carbonate crystals, and the sand has large compactness and high strength, while the sand with large particle size is easy to cause the generated calcium carbonate crystals to adhere to the particle surface, resulting in less contact between particles, which cannot effectively play a role in cementation, so the strength is low [22]. Amarakoon et al. [23] found that the best range of average particle size of sand is
0.6mm~1.2mm, in the sand with average diameter of 0.2mm, because bacteria can not completely catalyze urea hydrolysis, the output of calcium carbonate is the least, and the strength is the lowest, only 1.4MPa. In addition, the change of particle size also affects the cohesion, internal friction angle and shear strength of sand, with the increase of sand particle size, the cohesion of reinforced sand sample is no longer zero, and the internal friction angle increases slightly, and the shear strength increases exponentially [24].

3.4. Curing Method
Three methods of grouting, soaking and spraying are mainly used to solidify the sand, according to the comparison of previous experiments, it is found that the three methods have their own strengths and weaknesses. Among them, the reinforcement effect of pouring cement solution step by step at a lower rate is better than the immersion method, which reduces the sand saturation, and makes the calcium carbonate precipitation distribution more uniform, so it has higher unconfined compressive strength [25]. However, Andres et al. [26] found that the unconfined compressive strength of unsaturated sand treated by immersion method is higher than that of saturated sand treated by grouting method. Gao et al. [27] found that compared with the immersion method, the calcium conversion rate of sand solidified by spraying method is higher, up to 89.7%, at the same time, the generated calcium carbonate precipitation can be cemented into layers on the surface, which reduce the permeability of soil, and improve the strength of soil.

3.5. Chemical Treatment Method
There are two injection methods of bacterial liquid or cementing liquid, namely single injection and multiple injection, a large number of test results show that the treatment method of multiple injection is better. When the number of bacteria is the same, the reinforcement effect of multiple injection of low concentration bacterial solution is better than that of one injection of high concentration bacterial solution, because low concentration bacterial solution is not easy to cause flocculation, and the activity maintains for a long time, resulting in more and larger calcium carbonate crystals, which can more effectively enrich the pores between sand particles [28]. Direct injection of a single high concentration nutrient solution will rapidly precipitate calcium carbonate and block the pores between particles, resulting in uneven distribution of calcium carbonate at the upper and lower ends of the sand column, weak cementation effect and low strength [29]. Cui et al. [30] found that the unconfined compressive strength of sand samples solidified by injecting cementitious fluid in a combination of multiple concentrations is significantly higher than that of sand samples injected with cementitious fluid in a single concentration, and the sand can have higher strength with less grouting times.

4. Research on Engineering Application of MICP Technology

4.1. Sand Reinforcement
Van et al. [31] carried out grouting reinforcement for large volume sand columns, the test results show that the uniaxial compressive strength of sand has been significantly improved, up to 12MPa. Stabnikov et al. [32] conducted grouting test on the sand layer under the foundation, the content of calcium carbonate in the solidified sand is as high as 6%, which is strong enough to carry out drilling, pipeline laying and other construction. Whiffin et al. [33] used microorganisms to solidify the 5m long sand column, the test found that the uneven distribution of calcium carbonate precipitation caused by unbalanced grouting, and the strength of the solidified sand column is different, the closer to the grouting mouth, the higher the strength.

4.2. Blocking and Anti-seepage
Ferris et al. [34] conducted plugging test on sand by using MICP technology and found that the porosity of soil decreased, the permeability decreased and the plugging effect was good, and it is very suitable for use in oil exploitation and plays a role in improving efficiency. Van et al. [35] applied
microbial mineralization plugging technology to subgrade treatment to strengthen the soft and permeable soil under the subgrade, enhance the anti-seepage performance and effectively ensure road safety. Ma et al. [36] solidified by mixing microbial treatment solution and calcareous sand, and found that after treatment, the permeability of loose sand decreased to the same level as that of dense sand, the critical hydraulic gradient also increased significantly, and the seepage failure mode changed from piping to flowing soil.

4.3. Crack Repair
Chen et al. [37] used lightweight aggregate as the carrier of Pasteurella in concrete to increase the bacterial survival rate, successfully induce calcium carbonate crystal deposition, and effectively fill and repair small cracks in concrete. Lee et al. [38] injected bacteria and nutrient solution with calcium carbonate precipitation capacity into concrete to make its cracks self heal, greatly prolong the service life of concrete and improve durability. Khaliq et al. [39] directly incorporated Bacillus subtilis into concrete and penetrated into two carrier materials, graphite nanosheet and lightweight aggregate, the results show that the former is suitable for short-term crack repair and the latter is suitable for long-term crack repair.

4.4. Contaminated Soil Treatment
Wang et al. [40] induced calcium carbonate precipitation by Pseudomonas Schneider, and the heavy metal lead ions in the soil also precipitated, with a removal rate of more than 97%. Kumari et al. [41] used Bacillus cereus to treat CR contaminated soil, the Cr content before treatment was 7.5–18mg/kg, and the Cr content after treatment was only 0.34–0.65mg/kg, so its effect of removing heavy metal Cr was excellent. Zhu et al. [42] used MICP technology to remove nickel from highly industrial polluted soil, after treatment, the concentration of nickel in the soil was reduced from 900mg/kg to 38mg/kg, because the radius of nickel ion was close to that of calcium ion, which combined with carbonate ion to form precipitation.

5. Conclusion
Microbial induced calcium carbonate precipitation technology is a multidisciplinary achievement of microbiology, geotechnical engineering and so on. It is an eco-friendly and sustainable emerging technology. Compared with cement grouting reinforcement, it has better curing effect and wider application scope, and microbial mineralization reaction can be controlled. So far, this technology has achieved good results in engineering application. It is believed that with the in-depth research and continuous improvement of MICP technology by scholars at home and abroad, MICP technology can be widely used in more projects instead of traditional reinforcement methods in the near future.

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