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Experimental investigation of solidifying desert aeolian sand using microbially induced calcite precipitation

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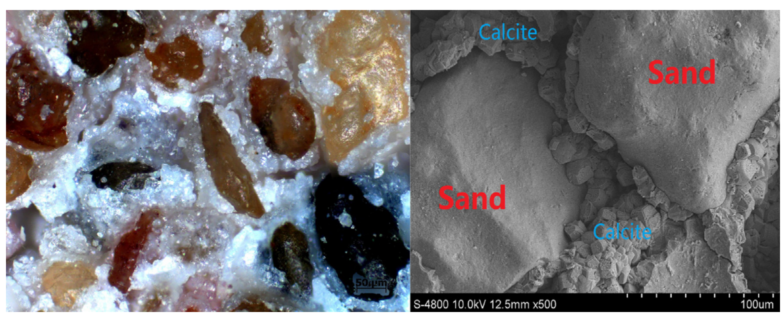
HIGHLIGHTS

- Engineering properties of desert aeolian sand can be improve by MICP technique.
- Concentration of solidification solution can affect properties of solidified sand.
- The UCS increase and permeability reduction due to $CaCO_3$ content increase.
- Calcite crystals cover on the particles surface and fill the pores.

GRAPHICAL ABSTRACT



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ABSTRACT

In this study, five different concentrations of solidification solution (0.5, 1.0, 1.5, 2.0 and 2.5 mol/L urea-$CaCl_2$) were used to solidify desert aeolian sand by microbially induced calcite precipitation (MICP). As the concentration of solidification solution increased, the $CaCO_3$ content increased, sand density increased, permeability was reduced and the unconfined compressive strength increased. Formation of $CaCO_3$ was the primary cause of changes in the sand's properties. Specifically, $CaCO_3$ filled the pores between the sand particles and the pore volume decreased. The $CaCO_3$ formed in response to low concentrations (i.e., 0.5–1.0 mol/L) and high concentrations (i.e., 1.5–2.5 mol/L) of urea-$CaCl_2$ solution played different roles in solidification of the structures.

1. Introduction

Desert aeolian sand is formed in areas with arid and semi-arid climates, such as northwest China. This material has a loose structure, no cohesion, uniform particle size, and poor self-stabilization, making it difficult to compact. Therefore, it must be strengthened before use as a foundation for roadbeds and other buildings [1,2]. The traditional methods of strengthening aeolian sand are mechanical compaction and solidification by curing agents [3–7]. Most curing agents are based on cement, as reported in previous studies. Luo et al. [8] investigated concrete made with dune sand and found that the very fine particles of the sand modified the properties of concrete via different mechanisms depending on the sand-cement ratio. Al-Aghbari and Dutta [9] investigated the potential for improving the engineering properties of desert sands in the Oman using cement and found that cement stabilization imparts substantial strength to desert sand, making it suitable as a layer in highway pavement for the base course. In another study,

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Al-Aghbari et al. [10] showed that the bearing capacity provided by mixing the sand and cement was sufficient to support a low-to moderate-rise building. However, organic chemical curing agents have somewhat high toxicity [11]. In contrast, microbially induced calcite precipitation (MICP) has many advantages, such as inducing increased strength, reduced permeability, energy savings and extensive environmental adaptation. It is a promising way to sustainability [12].

In 1973, Boquet et al. [13] found that soil bacteria induced the mineralization of calcium carbonate crystals during metabolism, which led to extensive research of the mechanisms involved in MICP and its potential applications. Microbially induced calcite precipitation (MICP) is an extensive biological mineralization process in nature. A series of chemical reactions in sand are induced and controlled by microbial metabolism, thereby solidifying the loose sand particles into a more solid structure with associated strength [12,14]. *Sporosarcina pasteurii*, which are urease-producing microorganisms that decompose urea efficiently, are commonly used to induce calcium carbonate precipitation during MICP. The MICP process involves complex biochemical reactions that employ urease produced by bacteria attached to the surface of sand to promote hydrolysis of urea and produce CO_3^{2-}. The CO_3^{2-} then reacts with Ca^{2+} in the external environment to form cementitious calcium carbonate between the surface of loose sand and granules. The reaction formulas are as follows [12,32]:

$$CO(NH_2)_2 + H_2O \rightarrow 2NH_3 + CO2 \quad (1)$$

Bacterial metabolic activity produces an abundance of urease, which acts as a catalyst to generate large amounts of ammonia (NH_3) and dissolved inorganic carbon.

$$2NH_3 + 2H_2O \leftrightarrow 2NH_4^+ + 2OH^- \quad (2)$$

$$CO_2 + 2OH- \leftrightarrow HCO_3^- + OH^- \leftrightarrow CO_3^{2-} + H_2O \quad (3)$$

With the hydrolysis reaction, alkalinity accumulates in the proximity of bacterial cells.

$$\text{Cell-}Ca^{2+} + CO_3^{2-} \leftrightarrow \text{Cell-}CaCO_3(s) \quad (4)$$

Carbonate precipitate forms on nucleation sites (bacterial cell surfaces), where CO_3^{2-} reacts with Ca^{2+}. During biochemical reactions, the bacteria play two core roles. First, they generate urease for urea hydrolysis, which creates a suitable alkaline environment for calcium carbonate precipitation through various physiological activities. The formation of calcium carbonate crystals then provides nucleation sites and Ca^{2+} enrichment to influence the morphology, deposition rate and yield of calcium carbonate [14–16]. In addition, bacterial and chemical solutions, treatment cycles, chemical concentration, sand types and particle size, concentration of bacterial solution, environmental conditions and experimental methods influence the bio-cementation effect [12,17–20]. Abo-El-Enein et al. [19] found that calcium chloride was a more suitable calcium source than calcium acetate and calcium nitrate.

Microbially induced calcite precipitation technology has been demonstrated to have great potential for use in a variety of applications [20], including environmental immobilization of heavy metals contaminated soils [21–23], reduction of seepage [24] and mitigation of erosion [25]. This method has also been used in surface treatments of concrete, the repair of concrete cracks and the strengthening of structures [26–30].

Many researchers have also conducted experiments to investigate the application of MICP technology in the stabilization of soil. Lin et al. [31] investigated the mechanical behavior of two types of Ottawa silica sands treated by MICP. Tests performed at 0.1 and 0.3 M calcium chloride resulted in specimens with average calcium carbonate ($CaCO_3$) levels of 1.5%–2.5% for 50/70 sand and from 1% to 1.6% for 20/30 sand. Triaxial sheer tests showed an increase in soil strength, even in response to 1% calcium carbonate. Jiang et al. [32] reported that MICP-formed carbonate precipitation increased the erosion resistance of sand-clay mixtures by directly absorbing and coating fine particles and bridging the contacts of coarse particles. Jawad and Zheng [33] found that MICP was effective for this type of sand and that it was more effective for sand with an initial water content of 0 (dry) with respect to increasing the strength, while the MICP was slightly better for sand with an initial water content of 100 (saturated) for the purpose of decreasing permeability. Kim and Youn [34] used five different microbes to precipitate calcite in cohesionless soils and found that the urease activities of four microbes were higher than that of *Sporosarcina pasteurii*. They also found that the relative density of cohesionless soils significantly influences the amount of calcite precipitation and that there is a weak correlation between urease activity and calcite precipitation. Sharma and Ramkrishnan [35] reported that treatment with the MICP technique led to a noticeable improvement (1.5–2.9 times) in the unconfined compressive strength of two different types (i.e., intermediate compressible clay and highly compressible clay) of fine grained soils, and that the strength increased as treatment duration increased. A model test using soil of up to 1 m^3 was conducted by Li Bing [36], who cemented Ottawa sand and filtration sand by grouting. In their study, the cementation efficiency was calculated to be 93% and the unconfined compressive strength of the treated sand was as high as 5977 kPa. Khan et al. [37] investigated the solidification of coral sand using the MICP method and showed that the unconfined compressive strength reached up to 20 MPa after 28 days of curing. Moreover, the compressive strength increased with increasing dry density and decreasing permeability.

Previous studies involved use of curing agents to solidify desert aeolian sand, which requires that the sand be mixed with curing agents. However, use of the MICP to solidify desert aeolian sand is an in-situ solidification method that involves adding a bacterial solution and allowing the solidification process to occur slowly. Previous researchers have mainly focused on the solidification of sand formed by hydraulic action, which comes from rivers and oceans. But the solidification of desert aeolian sand, formed by wind action in arid and semi-arid climates and treated with the MICP technique, has not been reported as much. Therefore, in this study, the MICP technique was used to investigate the solidification of desert aeolian sand by *Sporosarcina pasteurii* with five different concentrations of solidification solution. The feasibility and effectiveness of use of this process was then evaluated based on the density, permeability, calcium carbonate content, unconfined compressive strength and microstructure of the treated sand.

2. Materials

2.1. *Sporosarcina pasteurii*

Sporosarcina pasteurii were obtained from the American Type Culture Collection (NO. ATCC 11859). These organisms are chemotrophic heterotrophic aerobic gram-positive rods 2–3 μm in length that are basophilic, form round spores (diameter 0.5–1.5 μm), and show optimal growth at 25 °C–37 °C [38]. The organisms were cultivated on CASO agar (Table 1) prior to use in curing the aeolian sand. The agar was only added to solid medium.

2.2. Basic properties of aeolian sand

The desert aeolian sand used in the experiment was collected from the Tengger Desert in Shapotou District, Zhongwei, Ningxia Hui Autonomous Region, China. The sampling position is shown