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Understanding the variation of thermal conductivity of sands with bio-cementation and desaturation

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ABSTRACT

Shallow borehole thermal energy storage systems provide a reliable energy source that has been anticipated to supplement the energy grid in times of energy crisis and supply power to residences and commercial entities independently. However, the efficiency of such systems is reduced with desaturation, and the construction of deeper geothermal boreholes is often quite expensive in arid and semi-arid regions with deeper groundwater tables. This paper investigates the effect of biocementation on the thermal conductivity of fine sand for different saturation levels that can increase the efficiency of the system. The variation of thermal conductivity of soils was studied before and after treatment with dental biofilm that consists of *Streptococcus mutans*, sp. with suction varied from saturated state to nearly dry state. It was observed that biocementation enhanced the thermal conductivity of soils for all saturation levels, with the most prominent increase being near the optimum moisture content of the fine sand. This can potentially be utilized in shallow borehole thermal energy storage systems to improve efficiency and reduce costs.

INTRODUCTION

Biogeotechnics refers to the application of biological processes in geotechnical engineering problems to alter the engineering properties of soil. Biogeotechnics has gained traction in recent years due to the nature-inspired form of soil stabilization and potential sustainability. It has been used to tackle various forms of geotechnical problems like seepage control, preventing soil erosion, enhanced slope stability, liquefaction mitigation, and others (Dejong et al. 2013; Ghosh et al. 2024.; Lai et al. 2021; Martinez et al. 2022; Mitchell and Santamarina 2005; Samuel et al. 2021). The success of biogeotechnics for a particular problem depends on different factors. Biocementation or microbial cementation is a promising application in biogeotechnics due to its binding nature in soil regarding cellular chains of microbes (Ivanov and Chu 2008). The thermal conductivity of soils has been observed to increase with MICP treatment (Martinez et al. 2020a). The thermal conductivity of soil is influenced by factors such as mineral composition, the type of pore fluid, and various characteristics that affect the connectivity between particle contacts and fluid-filled pores, including density, grain size distribution, and saturation level (Martinez et al. 2020)This suggests there could be potential for applying biocementation other than MICP to improve the thermal and mechanical properties of soils surrounding energy piles. The effect of desaturation on the thermal conductivity of biocemented soils has not been studied in detail.

Borehole thermal energy storage (BTES) systems need high thermal conductivity and high heat capacity geomaterial in the vicinity of the geothermal boreholes to allow efficient transfer and storage of thermal energy between the soil and the borehole (Skarphagen et al. 2019)Traditionally, thermally enhanced grout in the form of bentonite and fine sand or chemically treated fine sand is used to improve the thermal properties of the shallow geothermal borehole system (Skarphagen et al. 2019) . Hydraulic conditions such as groundwater table level and its seasonal fluctuations also affect the efficiency of the BTES system. There is a significant concern regarding the observed low thermal conductivity of soils under unsaturated conditions. This may be of greater concern for regions with arid climatic conditions and deeper groundwater tables, where deeper BTES may be required to attain proper efficiencies. Quartz-dominant sand has high thermal conductivity, making it an effective medium for heat transfer (Yun and Santamarina 2008). In completely dry sand or under high matric suction, heat is primarily conducted through the solid particles, limited by their contact points (Liu et al. 2024). As water content increases, water menisci form at particle contacts, creating transitory water bridges that enhance heat conduction by increasing contact areas (Liu et al. 2024). This shifts heat transfer from particle-particle to particle-water-particle conduction, significantly boosting thermal conductivity. As water content rises further, the water bridges merge into a continuous membrane coating the particles, a stage known as the funicular regime (Lu and Dong 2015), which maximizes the thermal conductivity of sand. As moisture content in unsaturated sand increases, the sand gradually becomes saturated, shifting the heat transfer mechanism from solid-phase conduction to combined conduction by both the solid and liquid phases. This leads to a continuous rise in thermal conductivity as water content grows. However, the rate of increase in thermal conductivity slows as the sand approaches full saturation. In order to improve the thermal conductivity of sand in the saturated state, biocementation is one of the alternate solutions (Dong et al. 2015) as it increases the heat exchange performance (Martinez et al. 2013).

Novelty in the Study

One of the ways of novel biogeotechnics involves using dental biofilms (plaque) as sustainable soil stabilizers to enhance soil strength and alter the thermo-hydraulic-mechanical properties of treated soil. Dental biofilms, consisting primarily of various Streptococci bacteria, naturally adhere to our teeth (Kreth et al. 2008). The temporal development of dental plaque biofilm is driven by bacterial accretion through co-adhesion, and subsequent mineralization and cementation lead to calculus development (Lemos et al., 2013). When this calculus develops, it becomes hard. The composition of hardened calculus contains mainly calcium phosphate salts, and the extracellular matrix is associated with minerals (Loesche 1986). Additionally, the benefit of strength increase prompted the exploration of potentially integrating dental biofilms into fine sand to enhance soil thermal conductivity.

This study explores microbial product production, composition, and application by cultivating *Streptococcus mutans* sp. ATCC 10449 (Katsura et al. 2001) is a gram-positive pathogenic bacterium in fine sand formed through broth media. The experiments were conducted to identify the alterations in the thermal conductivity of treated soil over the drying curve. The soil water characteristic curve (SWCC) was also plotted to understand the unsaturated behavior of control (untreated) and microbially treated samples. The FESEM image was used to understand the attachment of bacteria at the intersection of the sand particles, which may help bind the soil particles together and fill the voids with bio-cemented materials that may enhance the thermal conductivity of soils.

MATERIALS AND METHODS

Soil Properties

The experimental study was performed on clean, fine sand. Table 1 presents the fundamental properties of the soil from the tests following the American Society for Testing and Materials (ASTM) standards. The soil samples were rinsed with 0.25 M HCl solution for 12 hours and then 0.25 M of NaOH for the same amount of time to remove leachable mineral salts as per the recommendations of other studies involving biocementation (Datta et al. 2022). Afterward, the sand was washed with deionized water and sterilized by autoclaving at 121° C for 30 minutes to remove any other microbes that might have interfered with the pilot study.

Table 1. Geotechnical properties of the soil used in this study

Properties	Standards	Fine sand
Specific Gravity, G_s	ASTM D854	2.65
Plasticity Index, *PI* (%)	ASTM D4318	NP
Coefficient of Uniformity (C_u)	ASTM D2487	1.56
Coefficient of Curvature (C_c)	ASTM D2487	0.92
USCS Classification	ASTM D2487	SP
Optimum moisture content, OMC (%)	ASTM D698	3.5%
Maximum dry density, MDD (g/cm^3)	ASTM D698	1.6

Measurement of Unsaturated Soil Suction

In order to determine the unsaturated properties of soil, HYPROP was used as a reliable experimental procedure for measuring the soil water characteristic curve (SWCC) for control and microbially treated soil. The HYPROP system uses an evaporation method, where two tensiometers measure the tension exerted by water within the soil column. The system tracks changes in the water content of soil over time at various tension levels (Peters and Durner 2006). The control sample and microbially treated fine sand were prepared using the same procedures as those prepared for thermal conductivity testing.

The grain size distribution of the control soil has been shown in Figure 1a. Figure 1b depicts the soil suction of both microbially treated and control samples of fine sand. The soil suction capacity increases for biotreated samples due to the cementitious effect between particles, resulting in a smaller size of the largest voids. The drier portion of the SWCCs depicts the higher moisture level in the biotreated sample, which may aid in maintaining a higher thermal conductivity as water has higher thermal conductivity than air.

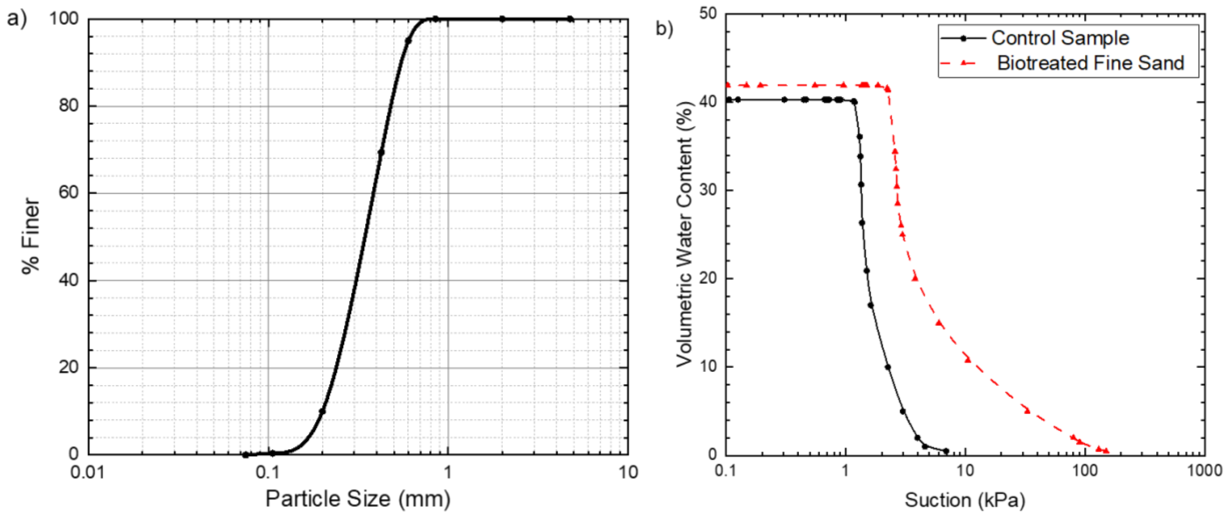

Figure 1. a) Grain size distribution of fine sand b) Suction of treated and control sample after Fredlund Xing model (Fredlund and Xing 1994)

Microorganism

In this study, a strain of aerobic bacteria, *Streptococcus mutans* sp. ATCC 10449, which had been isolated from carious dentine, was used. The strain demonstrated survival with minimal resources (Lemos et al. 2019). Depending on the nutrients available, this microbial strain can grow extracellular polymeric substances (EPS) with or without precipitating calcite through ureolytic or non-ureolytic processes (Koo et al. 2010). The isolated bacteria were cultivated on a solid nutrient agar plate at 30°C (Atanasov et al., 2023). The remaining strain was transferred into another vial and stored at 4°C for future use.

Preparation of Nutrient Media and Bacterial Growth

This bacterial strain was cultured under sterile aerobic conditions using brain-heart infusion broth (BHI; Difco, Detroit, USA). 1000 mL nutrient media was prepared and kept in the autoclave at 121°C for 15 minutes (Mir et al. 2021). The final pH value was 7.4. Firstly, the entire pellet was rehydrated with approximately 0.5 mL of broth. The contents were then aseptically transferred to a 5-6 mL tube of broth media.

To inoculate additional test tubes, 0.5 mL of the primary broth tube was transferred to these secondary tubes. The tubes were incubated at 37°C for 24 to 48 hours. The broth media consists of agar (15 g/L), brain extract (7.8 g/L), dextrose (2.0 g/L), disodium phosphate (2.5 g/L), heart extract (9.7 g/L), proteose peptone (10.0 g/L), sodium chloride (5.0 g/L). Suspensions of each microorganism were prepared and standardized in PBS to a concentration of 10^8 cells/mL (He et al. 2019) using a spectrophotometer (Genesys 20, Thermo Scientific). The cell densities of inoculum were counted at an optical density (OD) of 600 nm. The growth rate was consistent in the broth media for up to 15 days (Figure 2), whereas the media with bacteria was stored at room temperature. However, the OD cannot predict the strain growth, but as the density decreases after

9 days, it is assumed that the microbial growth decreases after 9 days. Future iterations may enhance the growth period.

The soil was inoculated with two different bacterial strains to showcase the growth of bacteria in soils to form aggregates or biofilms. *S. mutans* was selected for its biofilm-forming ability, and the soil bacterium *Bacillus pseudomycoides* was chosen for filament formation. Strains were cultured overnight in R2B, and Tryptone Soy broth, and 2 mL was added to 2g sterile soil in small Petri dishes (Figure 2(a)). *S. mutans* were incubated at 37°C, and the soil bacteria at 28°C. Triplet droplet plate count determined the population density of each. Briefly, 0.1g incubated soil was suspended in a sterile diluent, ten-fold dilutions were plated onto tryptic soy agar (TSA), and the culturable count was derived from MPN tables. *S. mutans* cell density was 3 x 10^8/g, comparing well to *B. paramycoides* at 9 x 10^8/g. This data shows that the dental bacterium *S. mutans* can grow to high densities in soil, close to those of endemic soil bacteria such as *B. paramycoides*.

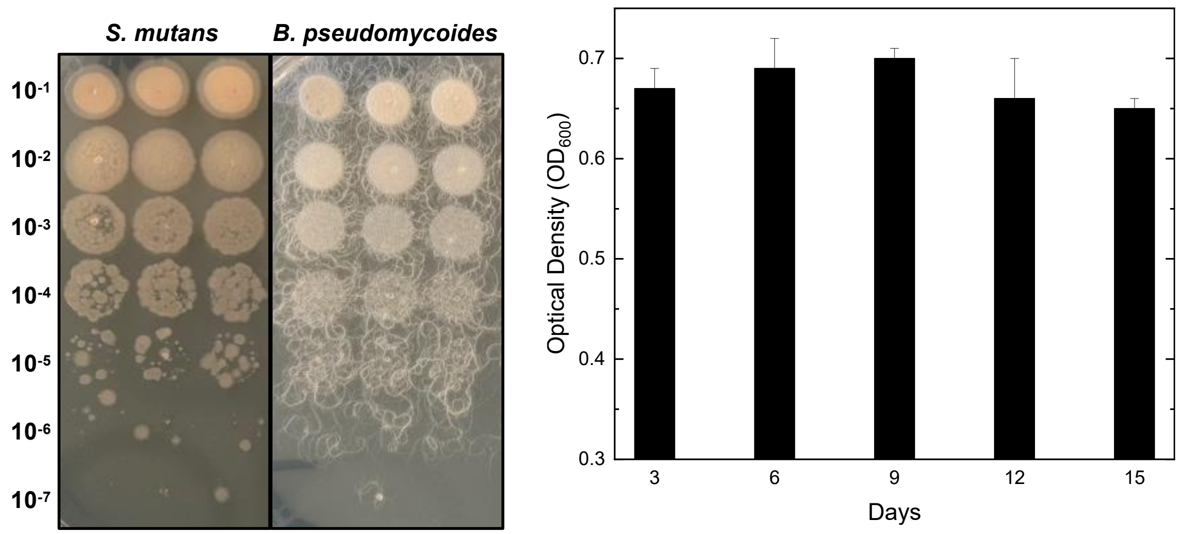

Figure 2. (a) Droplet plate count of *S. mutans* and the soil bacterium *B. pseudomycoides* after incubation in sterile soil for 5d. (b) Optical density of microbial growth

Sample Preparation and Inoculation of Bacteria

To study the variation of thermal conductivity with suction due to the formation of extracellular products like extracellular polymeric substance (EPS) and biocementation due to calcium phosphate deposition, laboratory specimens were prepared in a sample ring of 7.5 cm diameter with 5 cm height. EPS comprises carbohydrates, proteins, lipids, nucleic acids, and inorganic minerals such as carbonates, sulfates, silicates, phosphates, and iron and manganese oxides(DeJong et al., 2010). The thermal conductivity was measured using an automated system that measured thermal conductivity (λ) as a function of soil volumetric water content (θ). A TC-S70 sensor was inserted in the soil to measure λ (Figure 3). The correlation between λ and θ was determined by the data collected during the dryout process of the soil sample. The sensor was calibrated before using glycerin solution. The thermal conductivity of glycerin is 0.285 W/m·K at 25°C.

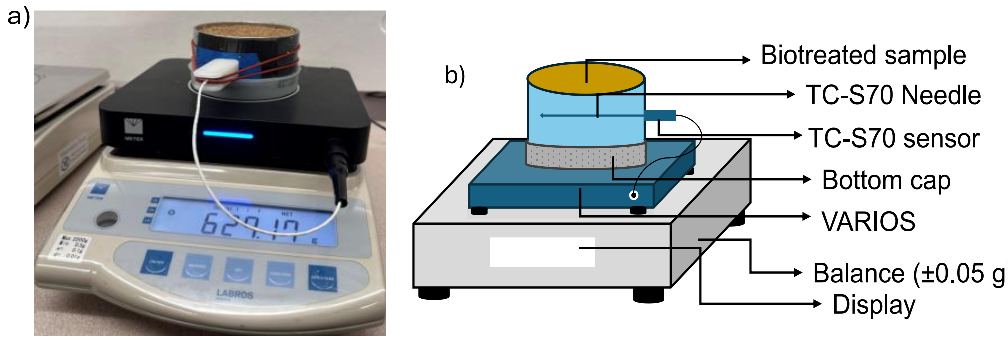

Figure 3. Thermal conductivity determination a) using sensor b) schematic diagram of the sensor

The thermal conductivity measurement principle relies on the transient line heat source method (Koniorczyk et al. 2019), where a heat pulse or periodic heat source is applied to the sample, and the resulting temperature difference of the sample is measured. Typically, the TC-S70 sensor includes a needle with a heater and a temperature sensor. A thermistor measures the temperature when a current passes through the heater inside the sensor needle. The thermal conductivity of that material can be determined by analyzing how the temperature of the sensor changes over time while the needle is in the soil. The needle is 7 cm long and directly contacts the surrounding soil, recording the soil temperature during the heating and cooling. Based on the line heat source theory, calculating the thermal conductivity of soil depends on the heating power (q) and the slope of the temperature increase with respect to the logarithm of time. Using these parameters, the thermal conductivity can be determined through the following equation (Cheng et al. 2021):

$$k = \frac{q}{4\pi a} = \frac{rI^2 \ln(t)}{4\pi \Delta T} \quad (1)$$

where k = thermal conductivity in W/m·K; q = heating power in W/m; a = slope for the rise in temperature over the logarithm of time; ΔT = temperature rise; t = time since the application of heat in seconds; r = the resistance per meter of the heating element; and I = current.

The control sample was prepared at the optimum moisture content and compacted by a tamping rod to attain the maximum dry density. The biotreated sample was prepared by pluviating sand grains into an autoclaved nutrient medium mixed with approximately 1 mL of bacterial solution. The specific nutrient medium was mixed with the soil samples. The specimens were prepared within a laminar air flow hood to prevent contamination, after which they were placed in a sterile incubator at 37°C for 12 hours. This incubation period allows the microbial population to attach to the surfaces of the sand particles via extracellular metabolic products(Ma and Marquis 1997). A freshly prepared bacteria-free nutrient medium was circulated through the specimens. To assess the initial bacterial growth and the subsequent increase in sample strength, the specimens were kept saturated in broth media for 24 hours and dried.

RESULTS AND DISCUSSIONS

Measurement of Thermal Conductivity

In Figure 4, the thermal conductivity of the control sample and the microbially treated sample are shown. Microbially treated samples show higher thermal conductivity than the control sample, as it indicates the cementation effect on the contact area of fine sand (Martinez et al. 2019). At the higher saturation point, the control samples of fine sand exhibit 2.6 W/m·K, whereas the thermal conductivity increases to 3.6 W/m·K (40% increase) in the biotreated fine sand. This indicates that the void between particles is reduced in biotreated fine sand. Thus, at higher saturation levels, which include the capillary and funicular regimes, heat transfer is primarily influenced by convection in the water phase and at the contact points between particles. In this context, small quantities of air have a limited impact on the thermal conductivity of soil. In terms of the control soil sample, at the same volumetric water content, the thermal conductivity is lower, which indicates that within this phase, small quantities of air present between the particles impact the thermal conductivity of the soil (Likos 2015). The thermal conductivity of the biotreated sample at the lower volumetric water content of around 3.5% (near the optimum moisture content) shows more promising results for the shallow geothermal energy system. As the moisture level increases, the thermal conductivity of the control sample increases, but at the lower moisture level of around 3.5%, the λ for the control sample is around 0.9 W/m·K.

In contrast, for the biotreated sample, the λ value is 2.1 W/m·K. Therefore, near the OMC, the thermal conductivity increase is nearly 2.3 times. Similarly, if the thermal conductivity is computed with suction by considering the SWCC shown in Fig. 1b, it could be observed that when the suction is increased to more than 7 kPa for control soil, the thermal conductivity is negligible (less than 0.1 W/m·K). However, for a similar suction level of 7 kPa for the bio-treated soils, the corresponding thermal conductivity is 2.7 W/m·K. In the study, the thermal conductivity of microbially treated sand was greater than 3 W/m·K at the lowest volumetric water content, thus improving the thermal conductivity by 50%. This shows that with climate change and anticipated prolonged droughts with deeper groundwater levels, it would be highly beneficial to have such bio-treated sands used as in-fill material for shallow borehole thermal energy storage systems. Additionally, EPS increases the affinity for water, which would aid in increased thermal conductivity in bio-treated sands.

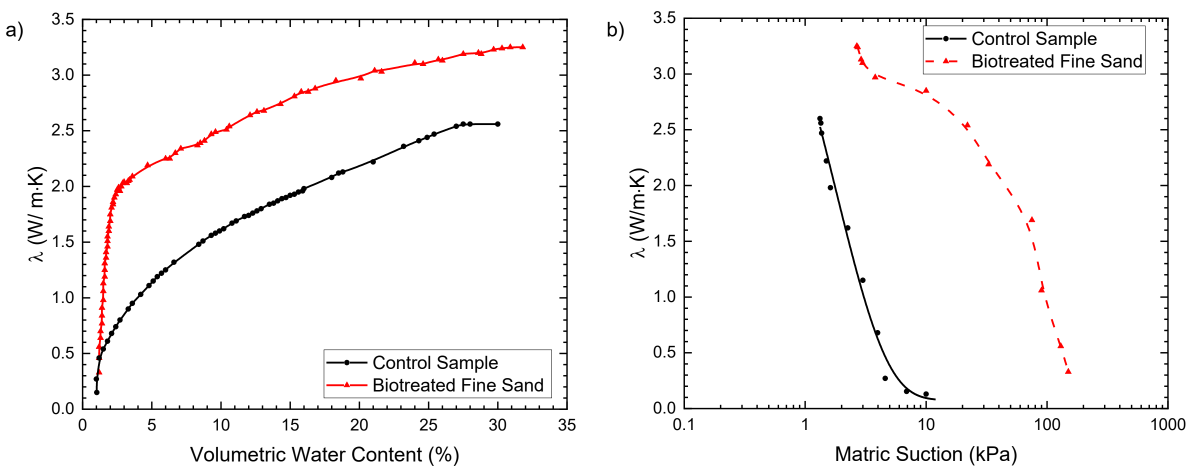

Figure 4. a) Thermal conductivity of control and biotreated sample b) suction vs. thermal conductivity

Morphological Analysis

The Field Emission Scanning Electron Microscope (FE-SEM) images of control soil and *Streptococcus mutans*-inoculated sand samples are shown in Figure 5. In Figure 5 (a) shows the controlled sample with higher voids between the particles. Higher magnification of SEM images shows bridging of the particles in biotreated sand samples 5(b). Figure 5(c) confirms the location of biocementation in the treated samples.

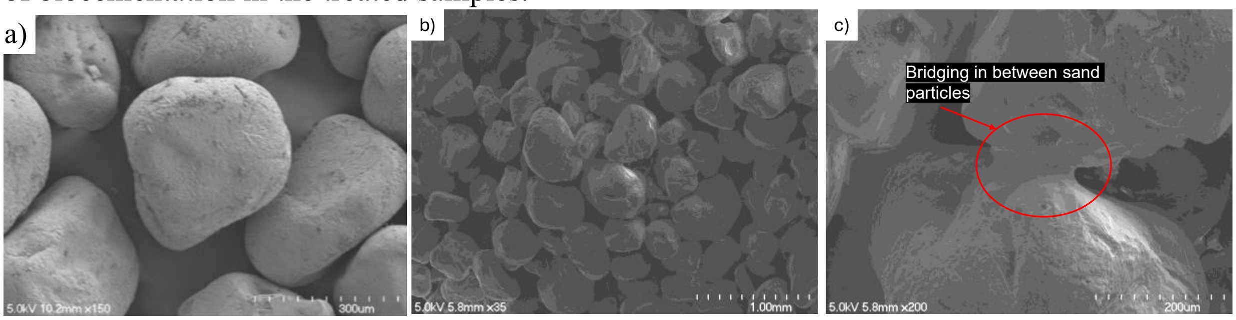

Figure 5. SEM images of a) sand particles (control sample); b) soil aggregation due to bio-cementation at the intersection of the soil particles; c) biocemented material in biotreated soils

CONCLUSION

In this study, the initial development of biofilms from the inoculation of *Streptococcus mutans* has demonstrated significant potential in enhancing the thermal conductivity of soil through biocementation processes. The result suggests that at low volumetric water content, the biotreated fine sand shows higher thermal conductivity, indicating the effectiveness of the biofilm in contributing to shallow borehole thermal storage energy. Since the BTES system requires higher thermal conductivity for transferring the thermal energy between the fluid in the pipes and the in-fill geomaterial, the biotreated fine sand could be a possible solution as it shows higher thermal conductivity than the control sample. Additionally, at the same suction level near the drier side of the soil, the biotreated sample demonstrated significantly higher thermal conductivity than the control sample. Morphological analyses further indicate these findings by revealing the soil aggregation at the interface of the sand particles and by filling the voids, a key indicator of successful biocementation. However, while these initial results are promising, they also highlight the need for further research. The modeling of these complex processes would aid in identifying the most suitable concentration and type of bacterial culture. The long-term durability study of the biotreated soil is crucial to ensure that enhancements in thermal conductivity are sustainable over time and economically viable.

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