Experimental Study on Thermal Conductivity of Sand Solidified by Microbially Induced Calcium Carbonate Precipitation

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Abstract. Soil thermal conductivity is relatively low in low saturation ranges in arid regions, resulting in low heat transfer efficiency of ground source heat pump (GSHP) systems. In this study, thermal conductivity of sand solidified by microbially induced calcium carbonate precipitation (MICP) was measured at different saturation levels. The test results reveal that the thermal conductivity of MICP treated sand increases with the increase in saturation degree (Sr), and the increasing rate gradually decreases. Use of the MICP technique not only increases the thermal conductivity of sands, but also reduces the influence of saturation degree on sand thermal conductivity when Sr is less than 0.22. This study provides a new research direction for the MICP technique and a technical reference for GSHP applications.

1. Introduction

Ground source heat pump (GSHP) is an energy-saving technology that uses shallow geothermal energy for heating or cooling purpose [1]. GSHP has been widely used in temperate and subtropical regions [2], but it has not been developed in arid areas because the low saturation conditions results in a lower soil thermal conductivity and therefore decreases the working efficiency of the GSHP system [3] [4]. There are many factors affecting soil thermal conductivity. Except for saturation degree, thermal conductivity of soil increases with the increase in dry density. The smaller the soil particle size is, the more contact points between the particles is, so the higher the soil thermal conductivity will be [5].

Microbially induced calcium carbonate precipitation (MICP) is a soil improvement technique that uses urease bacteria to hydrolyze urea to produce $\text{CO}_3^{2-}$ which reacting with $\text{Ca}^{2+}$ in environmental solution to form calcium carbonate ($\text{CaCO}_3$) precipitation in pore space in soils [6]. The permeability coefficient of MICP treated soils is reduced by an order of magnitude after one cycle of treatment [7]. Microscopic studies have found that the $\text{CaCO}_3$ can bind soil particles together [8]. In addition, the MICP technique has potential to improve soil thermal conductivity. Venuleo et al. improved the thermal conductivity of pure silica sand at different saturation conditions by using the MICP technique [9]. Wang et al. found that the thermal conductivity of dry MICP treated sand was increased by 120% compared...
to the untreated sand [10].

In this study, thermal conductivity of MICP treated sands under different saturation conditions were tested by the transient state method. The relationships between thermal conductivity of the treated sands and saturation degree, MICP treatment cycles and other factors were also investigated.

2. Materials and Methods

2.1. Test Sand
Test sand is poorly graded fine sand (SP). The median grain size ($d_{50}$) is 0.69mm, the coefficient of nonuniformity ($C_u$) is 2.51, the specific gravity ($G_s$) is 2.65, the coefficient of curvature ($C_c$) is 1.56, the maximum void ratio ($e_{max}$) is 0.79 and the minimum void ratio ($e_{min}$) is 0.59. The gradation curve of the test sand is shown in Figure 1.

Figure 1. Gradation curve of test sand.

2.2. Preparation of Bacterial Solution and Cementation Solution
The bacterial species used in this study is sporosarcina pasteurii (ATCC 11859). The bacterial was implanted into the nutrient solution in a ratio of 1 ml of the strain corresponding to 100 ml of the nutrient solution and incubated in a water bath thermostat at a temperature of 30°C and rotation speed of 130 rpm for 30 hrs. The composition and preparation method of the nutrient solution is shown in Table 1. The $OD_{600}$ value of the bacterial solution measured was close to 1.5. The cement solution is a mixture of Chlorium chloride anhydrous and urea at a concentration of 1 mol/L, which provides the necessary calcium source for the MICP treatment.

Table 1. The composition and preparation method of the nutrient solution.

| Purified water | Tryptone | Soya peptone | NaCl | Urea | pH | High temperature disinfection | Disinfection time | NaOH of 5mol/L |
|---------------|----------|--------------|------|------|----|------------------------------|------------------|---------------|
| 400ml         | 6g       | 2g           | 2g   | 24g  | 7.5| 121°C                        | 20min            | 800ul         |

2.3. Preparation of MICP treated Sands.
Four sand samples with a diameter of 3.9 cm and a height of 5.0 cm were respectively labeled as No. 0 to No. 3. The sample No. 0 is the untreated sand, and the samples No. 1 to No. 3 are respectively the MICP treated sands corresponding to treatment cycles from one to three. The procedures of sample preparation are as follows: (1) 60 ml of purified water was injected into each sand sample from the bottom with a peristaltic pump at a perfusion rate of 5 mL/min. (2) 60 ml of the bacterial solution was injected into the samples (No. 1 to No. 3) at the same speed. (3) After 2hrs, 60 ml of cementation solution was injected into the samples (No. 1 to No. 3) at the same speed and direction. The sand samples were
left to stand for 6 hrs. Steps (2) and (3) is the entire process of one MICP treatment cycle. The steps were repeated to prepare samples No. 2 and No. 3. (4) The samples were then cured at a constant temperature of 30 °C for 7 days. The dry density of samples No. 0 to No. 3 are 1.58 g/cm³, 1.58 g/cm³, 1.58 g/cm³ and 1.58 g/cm³, respectively. The samples was saturated by a vacuum pump according to the GB/T 50123-1999. Then, the water in samples was evaporated under room conditions to obtain different saturation degrees, and the corresponding thermal conductivity was tested.

2.4. Measurement of thermal Conductivity
In this study, a double probe sensor was used for measuring thermal conductivity of MICP treated sands as shown in Figure 2 [11-13]. The result of repeatedly testing the thermal conductivity of glycerol with it does not exceed 5% of the actual thermal conductivity of glycerol (i.e. around 0.358 W m⁻¹K⁻¹), so the sensor is demonstrated to have a high measurement accuracy.

The test device is shown in Figure 3. The wire of the thermal probe is connected to the programmable DC power supply (IVYTECH 3605). The current is applied by the resistance wire to heat the sand samples. The thermocouple is connected to the temperature readout unit (TC-08), and the temperature data is recorded by a data acquisition terminal (Picolog recorder).

![Figure 2. Schematic of the double probe sensor (unit: mm).](image1)

![Figure 3. Schematic of experiment device for thermal conductivity measurement.](image2)

Firstly, the ambient temperature was set as 25 °C and the temperature difference between the sand column and the environment as within 1 °C. The temperature acquisition time was set as 90s and the acquisition interval as 1s. Then, start the temperature measurement and turn on the power supply to 0.15A DC to heat the sand column for 15s. This step was repeated every 0.5 hrs for a total of 3 measurements. Then took the average of three test results as the thermal conductivity. Tested three times in the same way every 12hrs to obtain the thermal conductivity at corresponding saturation. When no significant change in saturation, the sand columns were dried at 70 °C for 3hrs and then the thermal conductivity was tested. Repeated the drying and test until the sand column was completely dry.

The saturation degree is calculated according to equation 1:

\[
S_r = \omega G_s e^{-1}
\]  

(1)

where \(\omega = (m-m_d)/m_d\) is the moisture content of the sand (%); \(G_s\) is the specific gravity of the soil particles; \(e\) is the void ratio of the sands.

The corresponding thermal conductivity is calculated according to equation 2:

\[
k = \frac{q}{4\pi(T_m - T_o)} \left\{ Ei \left( -\ln \left( \frac{t_m}{t_m - t_0} \right) \cdot \left( \frac{t_0}{t_m} \right)^{-1} \right) - Ei \left( -\ln \left( \frac{t_m}{t_m - t_0} \right) \cdot \left( \frac{t_0}{t_m} \right)^{-1} \right) \right\}
\]  

(2)

where \(q\) is the heating power of the line heat source (W/m), \(T_m\) is the highest temperature of the temperature measuring probe (°C), \(T_o\) is the initial temperature of the temperature measuring probe (°C), \(t_m\) is the time corresponding to \(T_m\) (s), \(t_0 = 15s\), \(Ei(x)\) is the exponential integral.
3. Results and Discussion

The relationships between the thermal conductivity of the sand and the saturation degree is shown in Figure 4. Compared with the dry sand, thermal conductivity of the sand (No. 1 to 3) at the fully saturated condition was increased by 382.57%, 228.49%, 212.39% and 203%, respectively. The thermal conductivity of sand is significantly improved with the increase in saturation degree, which is consistent with the previous studies[4][14]. This is because the thermal conductivity of water (about 0.59 W m⁻¹K⁻¹) is much higher than that of air (about 0.026 W m⁻¹K⁻¹). When the saturation degree is increased, water in the pores replaces the original air, then the heat transfer efficiency in sand is increased so that the \( k \) value is increased.

The empirical model of the normalized soil thermal conductivity with respect to saturation proposed by Johansen et al. is shown as equation 3 [15]:

\[
k_r = \frac{(k - k_d)}{(k_s - k_d)}
\]

where \( k_r \) is the normalized thermal conductivity, \( k_s \) is the thermal conductivity of soil at saturation condition, and \( k_d \) is the thermal conductivity of soil at dry condition.

Cote and Konrad proposed the relationship of \( k_r \)-\( S_r \) as equation 4 [4]:

\[
k_r = a S_r / (1 + (a - 1) S_r)
\]

where \( \alpha \) is the coefficient accounting the soil type effect (coarse sand, fine sand, silt, clay, etc.) on the \( k_r \)-\( S_r \) relationship. The recommended value of \( \alpha \) is 4.6 for gravel and coarse sand, 3.55 for fine sand, and 1.69 for silt and clay.

The test data were fitted by equation 3 and equation 4, and the \( \alpha \) values of sand were 2.54, 1.47, 1.43, 1.37, respectively. Combined with Figure 4, when \( S_r \) is less than 0.22, the \( k \) value of sand increases rapidly with the increase in saturation degree, and the \( k \) value of sand No. 0 increases faster than that of sand No. 1 to 3. It is known that the MICP technique can significantly reduce the sensitivity of sand’s \( k \) value to saturation under low saturation conditions.

The improvement in thermal conductivity of sand by the MICP technique is shown in Figure 5. The improvement is calculated according to equation 5:

\[
I = \frac{(k - k_u) k_u^{-1}}{100}\%
\]

where \( I \) is the thermal conductivity improvement of MICP treated sand (%), \( k_u \) is the thermal conductivity of untreated sand (W m⁻¹K⁻¹).

At the dry state, the \( I \) values are the largest which are 63.1%, 93.24% and 119.52% respectively for sands No. 1 to 3. The \( I \) value decreases significantly when the saturation increases from 0 to 0.2. When
the saturation is among 0.2 to 1, the $I$ values are relatively stable, approximately 13.13%, 24.07% and 34.43% respectively.

The relationship between the thermal conductivity of dry sand and the number of MICP treatment cycles ($N$) is fitted to get equation 6 and shown in Figure 6. The $k_d$ value of untreated sand is almost the same as that in Wang et al.[10] study, but the $k_d$ values of MICP treated sands are different. It may be caused by various factors such as test methods and size of the sand samples.

$$k_d = e^{(0.22\ln(N+0.43))} - 0.44$$

(6)

Figure 6. Effect of the number of MCP treatment cycles on thermal conductivity of sands at dry condition.

4. Conclusions

The thermal conductivity of MICP treated sand increases with the increase in saturation degree, and it is increased by 382.57% as compared with the untreated sand. When $S_r$ is less than 0.22, the thermal conductivity of treated sand is less sensitive to saturation than the untreated sand. The thermal conductivity of dry sand with three MICP treatment cycles is increased by up to 119.52%. When the saturation degree increases from 0 to 0.2, the thermal conductivity improvement drops sharply from the highest value. When the $S_r$ is greater than 0.2, the thermal conductivity improvement is stable. This study not only reveal great potential of the MICP technique in engineering applications, but also provide a solution for the application of GSHP in low saturation areas.

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