Effect of microbially induced calcite precipitation on soil thermal conductivity

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Efficiency of energy piles is strongly affected by soil saturation conditions: low water contents considerably decrease their performance thus limiting the possibility to extend their application to arid environments. This paper investigates the microbially induced calcite precipitation (MICP) technique as a potential means of enhancing the soil–pile heat exchange rates by improving the thermal properties of soil. The study puts the focus on measuring the thermal conductivity of untreated and treated sand at various degrees of saturation. Experimental results clearly show a significant improvement of the thermal conductivity of soil especially for low degrees of saturation. This enhancement is attributed to the mineralised calcite crystals acting as ‘thermal bridges’ between the soil grains, offering a larger surface area for heat exchange compared with the untreated material in which exchanges occur through smaller contact points.

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INTRODUCTION

Energy piles used as ground heat exchangers take advantage of the high thermal storage capacity of soil and have come to be seen as a cost-efficient, reliable and environmental-friendly technology that is spreading rapidly throughout the world (Laloui & Di Donna, 2011, 2013; Amatya, *et al.*, 2012; Akrouch *et al.*, 2015). The technology has met successful implementation in temperate climate zones, remains yet unexploited in hot, arid environments where the regional climatic conditions limit its possible advantages. Indeed, the air temperature, poor rainfalls and high evapotranspiration rates of these areas result in poor natural recharge of underground water and low saturation conditions, which alone can negatively affect the overall thermal properties of soil and thus the overall efficiency of energy piles. In particular, the decreasing heat storage capacity of soils as a result of soil desaturation, caused by the arid climate needs to be addressed to make energy piles a viable technology for hot areas.

This paper brings into focus the microbially induced calcite precipitation (MICP) technique as a potential solution for enhancing the thermal properties of soil for low saturation conditions. MICP is a biologically mediated method to induce in-situ cementation of granular soils (Mortensen & DeJong, 2011; Fauriel & Laloui, 2012) through the bacteria-driven urea hydrolysis, which in a calcium-rich environment results in calcium carbonate (CaCO_3) precipitation. So far the technique has been considered from a geotechnical point of view, solely to enhance the mechanical properties of soil (Whiffin *et al.*, 2007; Harkes *et al.*, 2009; Mortensen & DeJong, 2011; De Jong *et al.*, 2013). The increased strength and stiffness of

bio-cemented soils allow considering them even as construction materials (Bernardi *et al.*, 2014). The bio-cementation of soils has been mainly addressed at laboratory scale rather than in real-field applications. Van Paassen *et al.* (2009) provided evidence that supports the feasibility of the technique at a large scale for cementing bigger soil volumes. The main advantage of the technique lies in the low viscosity of the treatment solutions used, which facilitates the circulation of the reactants in a targeted area without causing erosion of the in-situ soil. In this framework, the effect of MICP on the thermal properties of soils is investigated, postulating that the propagation of the bacterial and reactant solutions is feasible at targeted zones. The goal of this paper is to elucidate the contribution of calcite precipitation to the increase in soil thermal conductivity (λ).

Numerical and experimental studies (Choi *et al.*, 2011; Akrouch *et al.*, 2015) have shown that under dry conditions the heat exchange may be reduced by up to 40% compared with that in fully saturated conditions. It is postulated here to compensate such reduction by inducing MICP, and hence altering the structural make-up of the soil; by the formation of intergranular calcite bridges, it is possible to increase the overall thermal connectivity of the solid matrix of the soil, and hence thermal conductivity. Soil thermal conductivity, as understood here, is the thermal conductivity of a multi-component medium composed of variable volume fractions of all the soil phases: air, water and solid. Several structural Q3 factors influence the apparent conductivity, λ : water content, mineral composition, bulk density, porosity and temperature (Becker *et al.*, 1992; Lu *et al.*, 2007; Wu *et al.*, 2014). MICP affects all the above factors, in particular, porosity, soil mineral composition and the average soil dry density. The latter increases with the amount of precipitated calcium carbonate mass (Whiffin *et al.*, 2007) and this increase is considered to reflect on the thermal conductivity of the treated soil, provided λ increases linearly with dry density (Yun & Santamarina, 2007).

The aim of this study is to validate this assumption by measuring and comparing the apparent thermal conductivity of untreated and MICP-treated sand samples at different degrees of saturation. Experimental observations (Farouki, 1981; Coté & Konrad, 2005; Smits *et al.*, 2009;

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Likos, 2014) suggest that the rate of change of thermal conductivity, with respect to saturation S , varies depending on the saturation regime. Three saturation regimes have been identified: the pendular regime ($S \leq 0.2$) characterised by the substantial variation in λ with respect to S ; the funicular regime ($0.2 \leq S \leq 0.9$), characterised by mild λ changes and the capillary regime ($S \geq 0.9$) characterised by no significant λ changes (Smits *et al.*, 2009, 2010; Likos, 2014). The authors will follow this classification.

EXPERIMENTAL DETAILS

Materials and sample preparation

Thermal conductivity of untreated sand specimens is measured and compared with that of an MICP-treated sample at different degrees of saturation. The tested material is pure silica sand (Itterbeck, Smals, the Netherlands) classified as SP (USCS ASTM 2487) with properties as shown in Table 1. Untreated sand samples are prepared in a plastic case under five-layer wet compaction to different degrees of saturation. The target dry density value is chosen to be equal to that of the sample to be subjected to MICP, prior to performing the injections. This choice allows comparing the pre- and post-treatment thermal properties once the MICP technique has been applied and the change has been evaluated. Details of the untreated samples and the plastic case are specified in Table 1.

To obtain the MICP-cemented sample, the bacteria strain *Sporosarcina pasteurii* (strain designation ATCC 11859) is grown under sterile conditions according to the protocol provided by the supplier (ATCC medium: 1376). The culture medium is centrifuged at 4000g to harvest vegetative cells from the consumed nutrients. The harvested culture has a cell concentration of 10^8 colony-forming unit per ml (cfu/ml). Cells are subsequently resuspended in 0.1 M calcium chloride (CaCl_2) solution and injected in batches alternatively at the top and the bottom end of a prepacked Itterbeck sand column with an initial dry density equal to 1.68 g/cm^3 . Bacteria are allowed an 8 h period to attach before introducing the urea- and calcium-rich solutions alternatively from the top and bottom of the column. Table 2 summarises the composition of solutions and the injection scheme.

Table 1. Sand, case and untreated sample properties

Untreated sand properties	
Grain density: g/cm^3	2.65
C_U	2.1
C_c	0.86
D_{10} : mm	0.1
D_{50} : mm	0.19
Silicon dioxide: %	>98
Dry density, ρ_d : g/cm^3	1.68
Porosity, n	0.37
Void ratio, e	0.58
Case dimensions	
Case height: mm	88.4
Case diameter: mm	97.8

The calcium carbonate precipitation is responsible for the cementation of sample with the precipitated nuclei filling the pores among the soil grains. The distribution of the calcium carbonate content inside the bio-cemented sample is measured across a section of the sample according to ASTM designation: D4373-14 (ASTM, n.d.) for 20 points in total. The properties of the obtained MICP-treated sample are listed in Table 3. To place the thermocouples in the bio-treated sample, two holes were opened using an electric screwdriver.

Measuring device and methods

Alrtimi *et al.* (2014) proposed a laboratory test to measure the thermal conductivity of soils based on Fourier's law of one-dimensional heat conduction at steady-state condition. They suggest that even though transient state procedures are simpler, the steady-state ones are considered more accurate. The proposed set-up is based on the guarded hot plate apparatus (GHPA) that is widely accepted as a primary apparatus to determine the apparent thermal conductivity (Xamàn *et al.*, 2009). A similar GHPA set-up is used in this study. The device (Fig. 1) includes two plates – both connected to an independent temperature-control system – responsible for maintaining the temperature constant on the boundaries of the tested sample, on its upper and bottom surfaces. The heat that flows longitudinally through the sample is independent of time. A thermal jacket is placed around the sample that serves as a heat insulation barrier. The two temperatures here referred to as $T_{\text{up,plate}}$ and $T_{\text{down,plate}}$ have been, respectively, set to 35 and 20°C. A heat flux sensor device connected to a voltage reader measuring instrument is put on the lower plate and the sample is placed above it. Provided that the heat flux Q is longitudinal, the sensor measures the heat flux Q/A across the sample according to relation (1) given by the manufacturer

$$C \times \text{measured voltage (mV)} = \frac{Q}{A} \left(\frac{W}{m^2} \right) \quad (1)$$

Finally, two thermocouples are placed at the two extremities of the sample, separated at distance L from each other and connected to a software system that records the temperature variation with respect to time. With reference to this scheme, in steady-state conditions, λ is computed as

$$\lambda = \frac{Q}{A} \frac{L}{(T_{\text{down}} - T_{\text{top}})} \quad (2)$$

On the basis of device specifications and the accuracy of its components, an error range is calculated for the parameters affecting the λ value. The obtained results concerning the untreated sand are validated using the empirical model of Coté & Konrad (2005). The value of the degree of saturation corresponding to each measurement of the thermal conductivity is determined at the end of the test, once the steady state is reached (approximately after 3 h). No data precisely corresponding to a fully saturated state are reported mainly due to the water leakage

Table 2. Composition and injection method of cementation solution used for the MICP treatment

Urea	Calcium chloride	Nutrient broth	Ammonium chloride	Number of batches	Input rate	Injection point	Period between batches
0.25 M	0.25 M	3 g/l	10 g/l	16	5 ml/min	Alternatively top/bottom	24 h

Table 3. Treated sample properties

MICP-treated sample properties	
Average calcium carbonate content: g/cm ³	0.13
Diameter: mm	57.40
Height: mm	75.97
Diameter of the holes: mm	3.30
Depth of the holes: mm	14
Initial dry weight: g	355.94
Dry density: g/cm ³	1.81

Fig. 1. (a) Schematic configuration of the measuring system

observed during sample preparation and also due to an expected evaporation during the test until the steady state is attained.

Through MICP a new mineral phase is formed inside the solid matrix, namely that of calcite. Scanning electron microscopy (SEM) is used to obtain an understanding of the fabric characteristics of the treated material.

EXPERIMENTAL RESULTS AND DISCUSSION

Figure 2 summarises the results obtained for the λ values with respect to the degree of saturation for the untreated and MICP-treated Itterbeck sand. As expected, the thermal conductivity values increase with an increasing degree of saturation S . Moreover, the obtained results are found to reproduce the general trend of the three saturation regimes described in the introduction section. The average obtained value of λ_{dry} (corresponding to $S=0$) is found to be equal to 0.30 W/mK. This value is in agreement with the Johansen (1975) and Lu *et al.* (2007) models that give $\lambda_{dry}=0.27$ and 0.30 W/mK, respectively. However, provided that λ within the capillary regime is often equal or close to λ_{sat} (Smits *et al.*, 2009; Likos, 2014), the value of thermal conductivity obtained for a degree of saturation equal to 88% ($\lambda_{88\%}=2.54$ W/mK) can be considered close to the λ value at saturation (λ_{sat}) and can be compared with the value obtained according to the model of Johansen (1975): $\lambda_{satJ}=2.56$ W/mK.

Table 4 summarises the standard deviation between the obtained values for the untreated material and those

Fig. 2. Comparison between thermal conductivity of the MICP-treated and untreated sand**Table 4.** Standard deviation of the obtained data for the untreated sand with respect to values predicted by models

Model	Standard deviation
Côté & Konrad (2005) fine sand	0.016
Côté & Konrad (2005) coarse sand	0.014
Lu <i>et al.</i> (2007)	0.033
Johansen (1975)	0.753
Square root model	0.029
Hu <i>et al.</i> (2001)	0.111

predicted by several semi-empirical models expressing λ as a function of S . Each of these models uses different fitting parameters. Results were compared with the models of Johansen (1975), Hu *et al.* (2001), Côté & Konrad (2005), Lu *et al.* (2007) and the square-root model. In particular, a good agreement is found with the models developed by Côté & Konrad (2005) and Lu *et al.* (2007). Having the lowest standard deviation, this latter model for coarse sand has been found to be the best to fit the measures proposed by authors.

The semi-empirical models used for comparison with the obtained λ values were based on the formulation offered by Johansen (1975)

$$\lambda = (\lambda_{sat} - \lambda_{dry})K_e + \lambda_{dry} \quad (3)$$

where K_e (the Kersten number) is a function of the saturation degree S that interpolates thermal conductivity between its maximum λ_{sat} ($S=100$) and its minimum λ_{dry} ($S=0$) values. It assumes different expressions depending on the considered model: for Côté & Konrad (2005) the expression becomes

$$K_e = \frac{\kappa S}{1 + (\kappa - 1)S}, \quad \kappa = \begin{cases} 3.55, & \text{fine sand} \\ 4.60, & \text{coarse sand} \end{cases} \quad (4)$$

Figure 3 presents the improvement (I) in the λ value calculated as follows

$$I (\%) = \frac{\lambda_{treated} - \lambda_{untreated}}{\lambda_{untreated}} \quad (5)$$

The obtained values for the MICP-treated sample are compared with the λ value of the untreated sand calculated according to the formula by Côté & Konrad (2005) [equation (4)].

Clearly, the effect of MICP treatment on thermal conductivity is most pronounced for dry conditions. In the

Fig. 3. Improvement in thermal conductivity due to MICP treatment

pendular state λ values exhibit significant increase passing from the untreated to the treated state. Changing from dry to saturated conditions the degree of improvement is decreasing, although remaining always at >25%. The increase in the average value of λ has been computed to be ~87%. Moreover, the obtained data show that the improvement in soil thermal conductivity can be quantified as a constant increase of ~0.87 W/mK of the λ values, corresponding to the untreated sand. A separate line illustrates this in Fig. 2 by modifying equation (3) as follows

$$\lambda = (\lambda_{\text{sat}} - \lambda_{\text{dry}})K_e + \lambda_{\text{dry}} + 0.87 \quad (6)$$

where K_e is given by equation (4).

At the pendular state, heat is transmitted through the solid phase through the contact points between the grains. Through SEM observations the calcium carbonate crystals are found to fill the interstitial space increasing the contact among the silica grains. In this case, heat is transmitted not through distinct contact points but through much larger contact areas, equal to the surface area of the calcite crystals attached onto the grains. A schematic representation of the above hypothesis is presented in Fig. 4. Figure 5 presents the SEM images obtained for a bio-cemented sample. Here, the interconnection due to calcite bonds between individual grains is observed. The authors use the term ‘thermal

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Fig. 4. Left: schematic representation of the contact points between sand grains in the case of untreated sand; right: contact areas due to the presence of calcite crystals bridging the sand particles in the case of MICP-treated sand

(a)

(b)

(c)

Fig. 5. SEM images obtained for the MICP-treated material: (a) calcite crystals are found to provide the crucial contact surfaces (arrows); (b) exposed surface of a calcite crystal that grew between two sand grains; and (c) calcite crystals filling the pore space among three neighbouring sand grains

bridges’ to highlight exactly the role of the precipitated calcite particles in increasing the energy storage capacity of the soil and providing a much greater soil volume for thermal exchanges between the structure and the surrounding soil.

The distribution of the calcite content was determined as described in the section experimental details. A total of 20 samples were taken as shown in Fig. 6 from the same section of the bio-cemented column. It appears that the calcite distribution is fairly uniform, without any strong

Fig. 6. (a) Distribution of the calcite content inside the MICP-treated sample expressed as the ratio of the calcite mass over the total dry mass of the sample; (b) and (c) twenty samples are taken from the same section of the cemented column

systematic bias, with slightly higher values at the sides. The average calcite content is found to be equal to 7.96% (w/w).

CONCLUSIONS

The effect of MICP treatment results in a strong increase of thermal conductivity of sand at different degrees of saturation. Comparing the thermal conductivity of the bio-treated sand with that of the untreated material shows that the MICP treatment can improve the thermal conductivity of soil by up to 250%. The enhancement is attributed to the formation of calcite crystals, which increases the contact areas between the soil particles and thus improves the heat transfer introducing 'thermal bridges'. MICP can thus offer a potential solution for extending the use of energy piles in areas, where otherwise the environmental conditions

would pose restrictions to an efficient heat storage system. A broader range of experiments towards this goal will be reported elsewhere.

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