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# Thermal conductivity of dried biocemented sand at higher calcification

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MICP-treated sand has been used for many soil stabilisation and erosion protection applications [10] with different bacteria types and paths of biocement generation. A novel application of the method is in the improvement of soil for energy geotechnics applications where a higher thermal conductivity (TC, λ) could be achieved by cementing and improving the existing contacts and developing new contacts among the grains with precipitated various calcium carbonate polymorphs formed during the process, such as calcite, vaterite and aragonite. Past studies, however, only a few, have shown a significant improvement in the TC of biocemented sand at dry and for the full range of saturation, incorporating a steady-state method [7], the transient method [5,6], and the transient plane source method (TPS) [11]. Venuleo et al. [7] studied the effect of 7.97% calcification content (CC) which led to a 250% improvement in TC in the dry state and 40% at the higher saturation range. Xiao et al. [11] presented a fitting equation to predict the TC with CC controlled by void ratio and coefficient of uniformity ($C_u$). Wang et al.'s theoretical model [10], developed by the soil model of Haigh [2], includes simplifications for the water content effect and geometric shape of soil phases, which has higher errors for low TC values and in lower saturation states. All the above studies are limited to lower calcite precipitation for TC measurement; however, higher calcite precipitation is reported in many studies where the mechanical properties of soil are improved [4]. Therefore, to shed light on the TC in the dried state, this study tries to measure the TC of MICP-treated sand in a dry state with a calcite content of up to 10.21%.

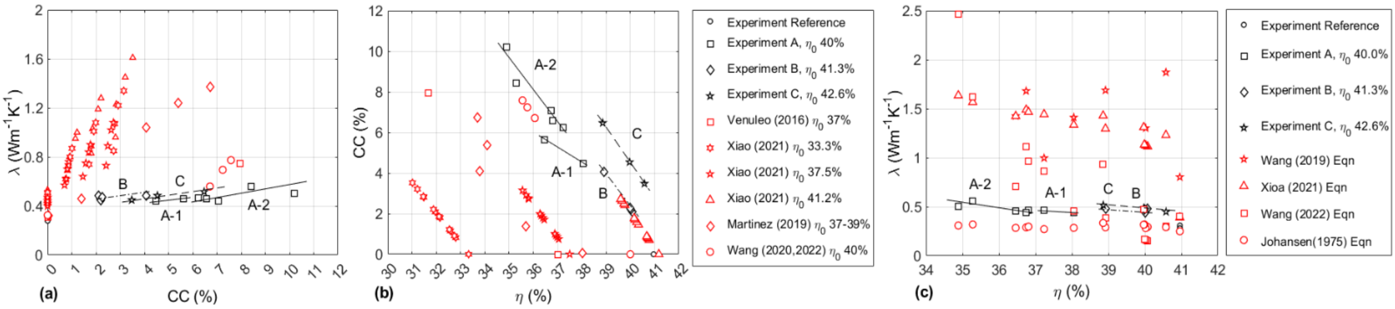


**Figure 1: TC of dry biocemented sand of current study (a, b) vs previous studies (c) vs other MICP-soil models.**

Medium-grained sand [1] with an average particle size of 0.79mm, specific gravity of 2.71, $C_u$ of 1.53, and density of 1.58±0.03g/cm$^3$ served as the reference. Bacterial and cementation solutions were mixed and injected with a continuous flow to the sand columns with a constant head and were renewed every 24 hours, 7-21 times. Post draining, the biocemented columns were accurately cut into the desired-sized discs and dried in the oven at 105°C for 24 hours. TC of the biocemented discs was measured in the dry state and at room temperature according to Hailemariam and Wuttke [3] and compared to other research [2, 5, 6, 7, 10, 11] in 3 different initial porosity groups ($\eta_0$ for A=40%, B=41.3%, C=42.7%). Group A was biocemented up to a higher cementation level, as depicted in Figure 1(a, b). As the $\eta_0$ in some studies [5, 7, 11] are initially more compact than the current study or have more fine materials inside (higher $C_u$ and less $D_{50}$), more TC with even less CC could be achieved. Limited experimental results [9, 10, 11], comparable with groups A-2 and B, are also shown. It appears that the same CC decreased void volume in [9, 11] more, which leads to higher TC compared to the current study. This is perhaps due to different gradation and fewer fine aggregates in the


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soil matrix with $C_u$ of 1.53 compared to studies with $C_u$ between 2-9.7 [9, 11], as mentioned in [11]. In the current investigation, the transition of the TC behaviour from part A-1 to A-2 with higher cementation can demonstrate a point (about CC of 6%) at which the CC form more effective bonds that abruptly increases the gradient of TC-CC graph from almost constant in part A-1 to 6.3% for part A-2 (up to 190% TC of reference). Finding this point for other groups needs a more comprehensive CC range than the current study. It is observed in A-2, B, and C that TC increased with increasing the CC, parallel with other studies [10]. Additionally, group C was able to offset the additional initial void available by having more CC to approximately the same TC as B. Less density increase rate ($I_d$) of group A-1 in Figure 1(c) suggests that the calcite condensation may have been less compact and effective bridges compared to that of groups B and C, which supports the slightly lower TC, even though it is a bit more initially compact. Figure 1(c) compares MICP-soil models available for the MICP-treated sands [8, 10, 11] and the Johansen soil model [12] for the results of the current study. Wang et al. [8] empirical model showed a scattered and overestimated result, perhaps because the model only considers the treated dried density and does not take the volume behaviour of biocementation as a bridge in the soil matrix into account. Xiao et al. [11] prediction with the closest fitting parameters to our case, given the available fitted parameters, overestimates the TC in the dry case for all samples. This can be due to the limited number of instances used for making this model, especially in the dry state and the unavailability of correct fitting parameters for $C_u$ less than 2. The model performed well for a similar sand from Martinez et al. [5] but cannot predict the results of Wang et al. [9]. Wang et al. [10] theoretical model also appears not able to predict the exact values for TC of dry state, and, for this study, it underestimates the TC for under 4% CC and overestimates it for over 4%. Perhaps the simplifications in the model can overestimate the thermal bridge size for TC below 1.2 W/m/K and low saturation and dry state. Hence, the model may not be able to provide correct results in the dry state [10]. The Johansen soil model [12] did not match our research either since it overestimates the TC for soils with a dry density between 1.57 and 1.65 g/cm3. It also needed to fit previous MICP-treated sand investigations [8].

Overall, neither the conventional soil models nor the theoretical or empirical equations from the literature can accurately predict the results of the dry state thermal conductivity measurement on the case studies of this research. It seems that there is an optimal CC among higher cementation levels that would be sufficient for creating more efficient bonds in the soil matrix, which rapidly elevates the TC. Therefore, more investigation on thermal conductivity in the dry state, especially on the higher cementation level impact, is needed to deduct a good prediction for different cases of MICP-treated sands.

**Contributor statement**

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