# Influence of Cementation Level on the Mechanical Behavior of Bio-cemented Slope Soil Treated by Surface Injection


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ABSTRACT: Bio-cementation has recently emerged as a novel soil stabilization technique that can improve mechanical behaviors of soil in a sustainable way. The contact cementation is induced by ureolytic soil bacteria through a set of bio-geochemical processes, leading to the formation of a stiff soil skeleton. The objective of this paper is to study the mechanical behavior of slope soil treated to varying cementation levels ranging from uncemented soil to heavily cemented sandstone like conditions. The unconfined compression test results suggest that the strength and stiffness of the soil increase with the increase in cementation level. As the cementation increased, the peak state was reached at lower axial strains, suggesting the increase in brittleness. Permeability results shows a linear decrease with the increase in cementation level. The bio-clogging mechanism also has been well demonstrated by SEM (Scanning Electron Microscopy). The outcomes of this study have deepened the understanding in specifying the desired treatment level for slope soil stabilization purpose.


## 1 INTRODUCTION

Bio-cementation is relatively a novel ground improvement method which shows great promise for various geotechnical engineering challenges. Bio-cementation can also be referred as microbial induced carbonate precipitation (MICP), in which the urease active bacteria could biochemically induce the calcium carbonate precipitates within soil matrix, preferentially at particle contacts. The crystallization results the contact cementation, surface coating and bridging through pore spaces (matrix supporting) (DeJong et al. 2010; Lin et al. 2016), leading to the increase in several engineering properties of soil such as stiffness, dilation, shear strength parameters, shear wave velocity and etc.

Up to now, several studies were performed to investigate the efficiency of this method for various geotechnical problems. Mitigation of liquefaction potential (Montoya et al. 2013), coastal protection (Nayanthara et al. 2019), settlement reduction (van Paassen et al. 2010), dust control (Meyer et al. 2011) and erosion control (Jiang et al. 2019) are some of the potential studies investigated. Recently, studies have demonstrated that the technique can be potentially applied for stabilization of slopes and embankments against surface degradation. Simulating the slope surface by column, Gowthaman et al. (2019a) demonstrated the feasibility of stabilizing natural slope soil by locally-isolated bacteria through surface injections. Following that, researchers performed the slope model tests to evaluate the cemented profile, suggesting that the particle distribution of residual soils drastically filter the bacteria cells at near-surface, limiting their transport to deeper zones (Gowthaman et al. 2019b). Through erodibility tests, few other researchers showed that the MICP could enhance the erosion resistance by several times compared to that of untreated slopes (Jiang et al. 2019; Salifu et al. 2016). It is therefore clear that the bio-cementation can be nondestructively applied by surface injection method for enhancing the cover condition of the slope.

Ordinary Portland Cement (OPC) is the widely used grouting material in stabilizing the slope soils, wherein the surface is sealed to immobilize the aggregates. It is the fact that bio-cementation (notionally the calcium carbonate) cannot be achieved to the strength levels of OPC; however, the technique can be a promising alternative with several unique merits such as environmental sustainability, retained permeability, cost effectiveness and revivability of strength.

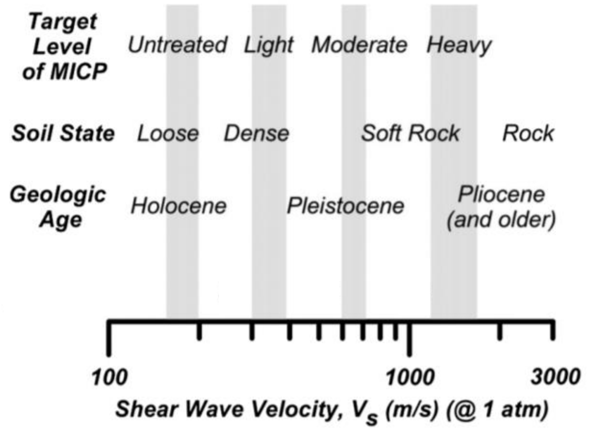


Fig. 1 Level of MICP, soil state and geologic age with shear wave velocity range (Montoya and DeJong 2015)

As previously defined by Montoya and DeJong (2015) (see Fig. 1), the bio-cementation could be achieved at various cementation levels from light to heavy, transforming the state of the soil respectively from loose to rocklike material. As per the states, the cementation levels can also be related to a broad range of geologic age, i.e., from young hydraulic fill to Pleistocene sand. It is worth noting that attentions should be carefully given in specifying the appropriate cementation level among the broad range based on the application purpose and requirement. Overtreatment as like hard rock material ($V_s \geq 1600$ m/s, see Fig. 1) leads not only to the increase in treatment cost, but also to the overburden pressure, resulting adverse effects on the stability of structure. For an effective design and implementation, a deeper understanding on the evolution of mechanical parameters with varying cementation levels is highly essential. Therefore, the objective of the study presented herein is to evaluate the mechanical properties of cemented slope soil across a range of cementation levels. The physical state of the soil is well elucidated within the chosen cementation levels. The UCS and permeability characteristics are also studied and discussed extensively herein.

## 2 TESTING METHODS

### 2.1 *Material and preparation of specimen*

The slope soil investigated herein was collected from the target erosion prone expressway slope in Hakodate (Hokkaido, Japan). The geotechnical properties of the soil are given in Table 1. $G_s$, $D_{50}$, $C_u$, $C_c$, *USCS*, *SP* and $D_{R,ini}$ are respectively specific gravity, mean particle size, coefficient of uniformity, coefficient of curvature, unified soil classification system, poorly graded sand and initial relative density. All the column specimens were prepared with similar relative density. The dimensions of the specimens were measured as approximately 30 mm in diameter and 60 mm in height.

### 2.2 *Soil bacteria and treatment*

The soil bacteria, *Lysinibacillus xylanilyticus*, isolated from the native soil were augmented to treat the soil. The isolation process of the bacteria can be found in the previous study (Gowthaman et al. 2019a). The bacteria were cultivated in ATCC 1376 ($NH_4$-YE) media at shaking incubation (25°C, 160 rpm). The bacteria were then harvested when the turbidity of the bacteria culture at the wave length of 600 nm, $OD_{600}$, is ranged between 4-4.5 (takes typically around 48 hours). Further detail on the biological response of the above soil bacteria can be acquired from Gowthaman et al. (2019b).

A two-phase surface injection strategy was used for the treatment. The harvested bacteria culture was injected at first, followed by the multiple number of cementation injections. The cementation media recipe consisted of $CaCl_2$, Urea and nutrient broth, at the concentration of 1 mol/L. All the solutions were simply applied at the flow rate of 4 mL/min and allowed to percolate under gravity and capillary effects. After the biological injection, few hours of retention were given prior to the cementation injections for the fixation of bacteria cells with soil particles. The cementation injections were performed every 24 hours. It should be noted that the volume of each injection was approximately equivalent to the pore volume of the specimen.

### 2.3 *Methods of assessment*

Different number of cementation injections (*N*) were performed to achieve different cementation levels. After the treatment, samples were flushed well using tap water to remove the soluble salts and chemicals. The molds were then cut carefully, and the samples were taken out for assessing the mechanical properties. Two different sets of specimens were prepared and treated identically for the (i) unconfined compression and (ii) permeability tests.

To study the strength characteristics, the unconfined compression tests using automated INSTRON 2511-308 load cell (USA), were performed on a set of specimens cemented to various levels, in accordance with the ASTM D7012 (2014). The samples were compressed at the rate of 0.036 mm/min until the critical state was achieved.

Table 1. Material properties

| $G_s$ | $D_{50}$ | $C_u$ | $C_c$ | USCS | $D_{R,ini.}$ | pH |
|---|---|---|---|---|---|---|
| 2.71 | 0.23 mm | 2.5 | 0.8 | SP | 60±2% | 6.99 |

The effect of cementation level on permeability characteristics of cemented specimens were also studied. The falling head permeability tests were performed using DIK 4000 system (Daiki Rika Kogyo Co., Ltd., Saitama, Japan), in accordance with the ASTM D5084-03 (2003). The specimens were saturated for 48 hours prior to the analysis.

Finally, the spatial distribution of precipitated $CaCO_3$ in all the tested specimens were measured by gauging the pressure of $CO_2$(g) released when the samples were reacted with HCl (2 mol/L) in a closed system, as suggested by (Fukue et al. 2011). For that, the specimens were equally divided into three sections across the depth and were separately reacted with HCl. Using the calibration curve, the mass of the calcium carbonate ($w_c$) is estimated and expressed as percentage (in terms of mass of the calcium carbonate divided by the mass of the uncemented soil).

## 3 RESULTS AND DISCUSSION

### 3.1 *Physical state of soil with varying cementation levels*

In this study, the evolution of physical and mechanical characteristics was studied across a range of cementation levels. The changes in the physical state of the soil were continuously monitored with the treatment quantity, i.e., across the varying cementation levels. Initially, the untreated slope soil is in loose state as young and fresh. When the treatment is applied, the $CaCO_3$ forms within soil matrix, cementing the particle contacts, eventually converting the separate soil particles to aggregated larger clusters as depicted in Fig. 2. Treatment levels (representing the number of cementation injections) were chosen arbitrarily within the target shear wave velocity range (from loose to soft rock ($V_s \leq 1600$), refer Fig. 1).

At the low treatment levels ($N$=1 and $N$=3), the particles are not well aggregated; lightly cemented clusters are clearly observed together with loose material (refer Figs 2-a and 2-b, respectively), suggesting that the quantity of precipitated carbonate is not adequate to provide strong connections. When the number of treatments is increased to 5 (Fig. 2-c), a moderately cemented soil structure is achieved, and the precipitated carbonate could be able to retain its initial shape under its self-weight. However, the sample bottom is not stable as top, and the soil particles appears to be easily detachable from the bottom specimen.

When the number of treatments is increased to 7, an entirely cemented stable skeleton could be achieved (Fig. 2-d). It is worth noting, that the shear-wave velocity of the specimen ($N$=7) is around 1000 ± 50 m/s.

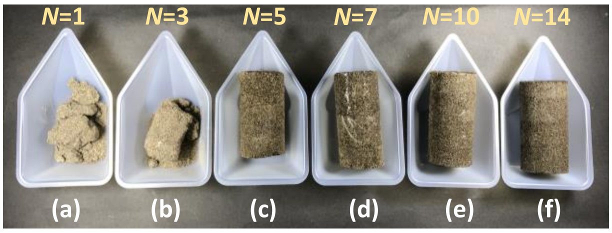


Fig. 2 Physical state of the soil with varying cementation levels

The specimens become more stable and stiffer, when the number of treatments is increased further ($N$=10 and $N$=14) (refer Figs 2-e and 2-f, respectively). Within this heavy treatment zone ($N \geq 7$), the quantity of precipitated carbonate appears to be facilitating strong bridges among particles, leading to a stiff soil skeleton. Aggregate stability is the most serious concern in slope soil preservation, and the physical states at these heavy cementation levels are likely to be more suitable and effective.

### 3.2 *Distribution of calcium carbonate in surface injection method*

As the bio-cementation is achieved by the surface injection method, it is very necessary to assess the distribution of the calcium carbonate and the homogeneity of treatment with depth. The slope soil is found to be consisting of negligible quantity of calcium carbonate material (less than around 0.2%).

Fig. 3 presents the distribution of calcium carbonate in all the cemented specimens, plotted against the normalized height. As expected, the average precipitated mass shows a general increase with the increase in treatment number ($N$). It is worth noting that all the specimens show a similar tendency that the precipitated calcium carbonate reveals a heterogeneity in the vertical distribution.

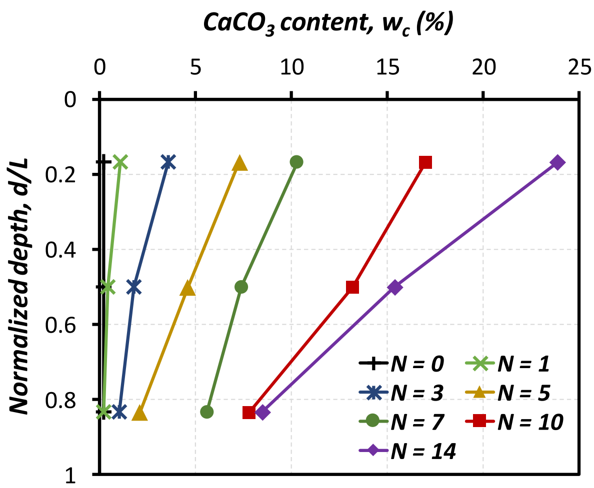


Fig. 3 Distribution of $CaCO_3$ with normalized depth ($d/L$) ($d$ is the depth measured from surface; $L$ is the total length of the specimen)

The highest mass of calcium carbonate is observed closer to the injection top for all the specimens, and this observation is in a good agreement with previous work (Cheng and Cord-Ruwisch 2014).

Fig. 3 also demonstrates that with the increase in the treatment number, the deposition rate of the calcium carbonate is higher at the top compared to that at bottom. As proved in the literatures (Gowthaman et al. 2019b; Martinez et al. 2013), the prime reason for this less uniformity is the distribution pattern of the bacteria. Transport of the bacteria is significantly determined by flow paths facilitated by soil pores. During the surface injection, more bacteria cells are filtered near the injection point due to the less pores in slope soil (fine sand consisting silt particles). As the liquid resources are supplied to the soil, reactions are induced rapidly at the zones with high bacteria concentration, leading to form the carbonates at high rates. At the time the solutions reach the specimen bottom, the resource concentration becomes less, resulting a less formation of calcium carbonate.

### 3.3 *Response of varying cementation levels to uniaxial compression*

A series of unconfined compression tests were performed to the treated samples. Fig. 4 presents the stress-strain behaviors of the specimens treated to varying average cementation levels ($w_{c,\,avg}$). $w_{c,\,avg}$ indicated herein represents the average of the three calcium carbonate measurements across the depths. As shown, specimens cemented to higher levels exhibit higher strength and stiffness compared to that of lightly cemented and uncemented soils of similar initial relative density. The response of untreated specimen is plotted as reference to compare the behavior of cemented slope soils. The peak and residual strengths increase with the increase in cementation level. However, the increase in the peak and residual strengths are not very significant up to the cementation level of 4.7% (up to around 1.4 times); particularly, the residual strength is found to be very close to that of untreated soil. Therefore, it is clearly understood that at lower cementation levels, the stress-strain behavior of slope soils is quite similar to the uncemented specimens.

On the other hand, when the average cementation level is increased to 7.8%, 12.7% and 16%, the peak strength increases, respectively by around 5.2, 17.6 and 58.5 times higher than that of uncemented one. Also, the higher the cementation level, the larger the initial modulus of the stress-strain response is observed, which is similar to several previous observations (Feng and Montoya 2016; Gowthaman et al. 2020).

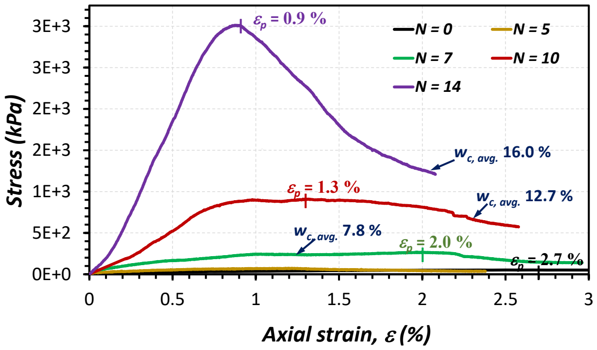


Fig. 4 Stress-strain behaviors of the slope soil treated to various average cementation levels

At higher cementation levels, there is a considerable increase in the residual strength also. Gowthaman et al. (2020) have observed the increase in effective friction angle during the shearing tests, demonstrated that residual strength is primarily attributed to surface roughness of the bio-cemented soil particles. Therefore, the increase in the critical state stress observed herein is probably due to the increase in the coated calcium carbonate.

The cementation appears to have a large influence not only the peak and residual strength but also the localization of corresponding axial strain (i.e., failure strain). The samples cemented to 7.8%, 12.7% and 16%, the peak was reached at the axial strains of 2.0%, 1.3% and 0.9%, respectively (Fig. 4), perceiving that the peak strength reaches at low axial strains as the cementation increases. This behavior is likely due to the stiffening effect i.e., the densified initial state of the specimen corresponding to the level of cementation.

The stress-strain response of uncemented slope soil exhibits the strain-hardening behavior. It is worth noting that as the cementation level increases, the behavior of slope soil transitioned from strain-hardening to strain-softening. Similar observations are also reported to bio-cemented sands in previous studies (Feng and Montoya 2016; Montoya and DeJong 2015).

### 3.4 *Hydraulic conductivity*

The hydraulic conductivity of the untreated specimen is around $2\times10^{-2}$ cm/s, which falls under the category of the clean sand (Craig 1983). Fig. 5 presents the variation of hydraulic conductivity with the magnitude of maximum and average precipitated calcium carbonate contents ($w_{c,max}$ and $w_{c,avg}$, respectively). It can be seen that the hydraulic conductivity of the slope soil linearly decreases (in log scale) with the increase in the precipitated carbonate content. Basically, the hydraulic conductivity of soil is largely determined by its void space (Martinez et al. 2013); the precipitated carbonate content increases as the number of treatment increases, resulting the void filling. When the soil is treated slightly ($w_{c,avg}$ of 0-3%), the reduction in hydraulic conductivity is negligible ($1\text{-}2\times10^{-2}$ cm/s), which is consistent with the observation reported by Do et al. (2017) for lightly cemented sand material.

When the soils are heavily treated ($w_{c,avg}$ of above 7%), reduction in hydraulic conductivity is significant; for example, the samples cemented to around 8% ($N$=5) and 13% ($N$=10), the reduction of hydraulic conductivity is about 70% and 85%, respectively. Also, up to around 90% of permeability reduction is observed when the sample is cemented to $w_{c,avg}$ of about 16%. Similar permeability observations are also reported by Achal and Mukherjee (2015).

As explained in the previous section, there is a non-uniformity of carbonate distribution in the treated slope soil. It is worth noting that in one-dimensional column specimen, the bulk hydraulic conductivity is controlled by the zone where the deposition of calcium carbonate is the highest, and therefore, the hydraulic conductivity is also plotted against $w_{c,max}$ (Fig. 5). When the permeability of the specimens reaches $10^{-3}$ cm/s, the flow of the resource liquids is significantly inhibited, leading to the retainment of the solutions on the specimens for many hours, sometimes to bio-clogging stage.

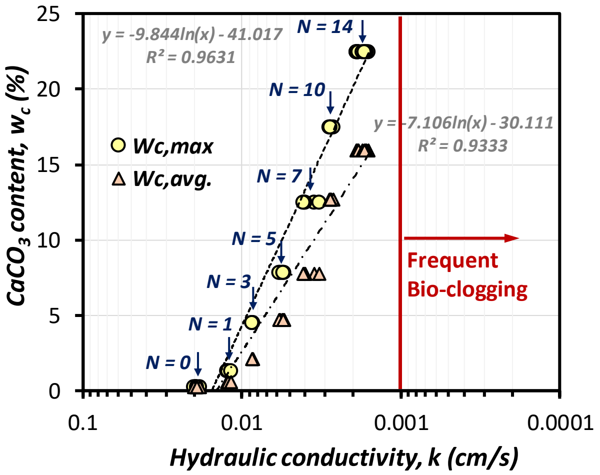


Fig. 5 Relationship between $k$ and $w_c$ ($w_{c,max}$ and $w_{c,avg}$ are the highest and average of the three measurements across the depths of the specimens, respectively)

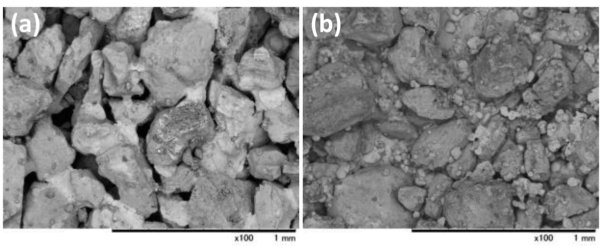


Fig. 6 Bio-cementation with (a) retained permeability (achieved typically) and (b) bio-clogged surface of the specimen (achieved during overtreatment)

## 3.5 *Bio-clogging in slope soil*

When the samples are treated by more than 15 injections of cementation solution, bio-clogging is frequently experienced. It should be noted that bio-clogging does not literally means that the entire voids in soil are filled by calcium carbonate. As observed earlier, the surface zone of the treated soil shows high carbonate content, revealing as the probable zone of bio-clogging. The continuous deposition in the above zone results the inhibition of flow paths, leading to bio-clogging stage.

Fig. 6 presents the SEM images of bio-cemented specimens' surface. It is clearly perceived that bio-cementation has the unique merit, the retained permeability (Fig. 6-a) even at heavy cementation levels (Fig. 6-a corresponds to $N$=14). In the surface injection method, filtration of bacteria at particle contacts leads to the preferential deposition of calcium carbonate at contact points. Unlike the sealings by conventional grouts like OPC, this mechanism holds the soil pores relatively open, and which are clearly visible at micro-scale (Fig. 6-a). On the other hand, overtreatment results sometimes bio-clogging (refer Fig. 6-b). It can be seen that the surface pores are almost filled by carbonate bio-cement. In this case, the infiltration of further liquid media is impossible, acting as an impermeable bio-crust as reported by Stabnikov et al. (2011). Considering the real field applications, sealing the slope surface by an impermeable bio-crust (bio-clogged surface) causes some adverse effects. Inhibiting the infiltration of storm water possibly results the water buildup on the treated slope surface, leading to additional overburden and sheet flow with high energy. Therefore, this study recommends a surface treatment with retained permeability, allowing certain quantity of storm water infiltration to control the water buildups.

# 4 CONCLUSIONS

The present study demonstrates that the bio-cementation technique has a large influence on improving the mechanical characteristics of slope soil. The physical and mechanical behaviors of slope soil cemented to varying cementation levels are studied herein, and the following conclusions are drawn.

- As the cementation level increases from light to heavy, the state of the soil transitions from loose to dense (i.e., soft-rocklike material).
- The increase in the bio-cementation level in slope soil results in high stiffness, peak and residual strength. However, the light cementation ($w_{c,avg}$ < 4.7%) shows only a limited improvement in strength, whereas the improvement is significant beyond the $w_{c,avg}$ of around 8%.

- As the cementation increases, the peak stress is reached at lower axial strains.
- The strain-hardening behavior is observed during the compression of uncemented slope soil, and as the cementation increases, the strain-hardening behavior transitions to strain-softening.
- The increase in cementation, the decrease in the permeability is observed. However, in surface injection method, bio-cement is preferentially deposited at particle contacts, which tends to retain the permeability.

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