MECHANICAL STRENGTH OF ORGANIC SOIL TREATED BY FIBER INCORPORATED MICROBIAL CEMENTATION

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Introduction

Within the past decade, the discipline of biogeotechnical engineering has been well established, in which the applications of microbial induced carbonate precipitation (MICP) method has become very popular for stabilizing gravels and sandy soils. Numerous investigations have been performed for various geotechnical applications such as ground improvement, slope soil stabilizations, erosion control, dust control, liquefaction control, etc [1–3]. In spite of considerable interests in MICP, the MICP investigations performed on organic soils are very limited, providing insufficient information on strength and mechanical responses of MICP treated organic soils.

Within the past couple of years, few researchers have started investigating the feasibility of treating organic soils. Canakci et al. [4] treated the peat by MICP using hydraulic injection, suggesting that 16% calcium carbonate precipitation increased the shear strength by around 30%. By performing the direct shear tests on organic silt, Widjajakusuma et al. [5] concluded that the MICP has increased the cohesion by 180-270% by the end of 28 days, but not the friction angle. The compressibility of organic soil also has been investigated, wherein the MICP reduced the coefficient of consolidation from 2 mm^2/min to around 1 mm^2/min [6]. However, previous studies suggest that the achieved strength in organic soils was different than that of the sands [4,6]. The typical MICP approach could improve the organic soils only up to a certain extent, although calcite was well precipitated; therefore, amendments in treatment strategy are highly essential to achieve the target strength in organic soils.

As the application of fibers in soil stabilization (particularly random distribution (RD) of short discrete fibers) has become more prevalent in recent past due to various merits such as moisture control, increasing frictional forces and interlockings [7,8]. Therefore, this study attempted to investigate the viability of fiber incorporated MICP on stabilizing organic soil in order to effectively provide tentative access on peat lands. Discrete bamboo fibers, one of the waste materials of bamboo industry, rich in both cellulose and lignin content over most of other natural fibers [7], have been chosen for this study.

Materials and Methods

Organic soil

The organic soil used in this study was obtained from Iwamizawa (Hokkaido, Japan). The sampling process is shown in Fig. 1-a. According to the Unified soil classification system (USCS), the soil is classified as organic peat. With the moderate decomposition, the peat is found to be falling under the category of hemic peat (Fig. 1-b). The fundamental chemical and physical analysis were carried out, and the results are presented in Table 1.

Table 1: The fundamental engineering properties of peat used in this study

Parameters	Values
Water content (%)	810 – 830
Density (g/cm^3)	1.8
Ignition loss (%)	65.8
pH	4.6 – 4.8
Coefficient of permeability	10^{-4} – 10^{-5}

Isolation and characterization of ureolytic bacteria

The isolation of ureolytic bacteria was performed to the peat soil sampled from 1 m depth. The isolation methods used herein are similar to those reported in previous work [9]. The isolated bacteria were then characterized by sequencing their 16S rDNA and comparing the results with the sequences available in the Apollon DB-BA 9.0 database, GenBank, DDBJ (DNA Data Bank of Japan) and EMBL (European Molecular Biology Laboratory).

Method of treatment

As the injection method has restrictions on microbial transport in peat soil, mixing method was incorporated in this study. First, the resources (calcium chloride, urea and sodium bicarbonate) were mixed at their solid state until they were completely dissolved in the moisture exists in fresh peat soil (no additional moisture was supplied), followed by the mixing of microbes. The ureolytic bacteria cultured at 30°C were cultivated after 48 hours, and their OD_{600} was adjusted to the value of around 10. In order to control the moisture addition, small volume of bacteria culture (around 5 mL for 150 g soil) were added and mixed well. Finally, the fiber material was introduced to the soil. In this study, the bamboo fibers (Fig. 1-c), the waste material of bamboo industry, were used as a tool for controlling the moisture of peat. The discrete bamboo fibers with the average size of 150-200 μm were mixed at different ratios to maintain the water content at different levels.

The treated soils were then cured at 30°C, and the mechanical strength of the specimens were measured by fall cone test method (in accordance with JGS 0142-2009) after 2 days (early strength) and 7 days (late strength). The amount of precipitated calcium carbonate was assessed by acid washing method suggested in many previous works [10,11]. The SEM analysis were also performed to study the microstructural characteristics and morphology of the treated peat soil.

Results and Discussion

Ureolytic bacteria

From the peat soil, three number of urease positive bacteria were identified (existence of ureolytic bacteria is less than 20% among the total bacterial inhabitant). Two bacteria were characterized as *Staphylococcus edaphicus* (PS-1) and *Oceanobacillus profundus* (PS-5), and PS-1 strains were used in this study to treat the peat soil. The activity of the bacteria was found to be around 0.1 mol/min/mL/OD_{600} at 30°C.

Figure 1: (a) Sampling peat soil, (b) appearance of peat soil and level of decomposition (c) SEM image of discrete bamboo fibers

MICP on peat soil
The undrained shear strength (C_u) of the untreated peat soil was less than 1 kPa (at the moisture content of 811.9%). As the preliminary stage, the MICP treatment (as explained in the methods) was performed to the fresh peat soil without incorporating the fiber material. Each of the resources ($CaCl_2$ and urea) mixed at the beginning was at 1 mol/L (calculated based on the gross volume of the soil).

Fiber incorporated MICP
Figure 2-a shows the improvement of peat when the fibers are implemented alone. It can be seen that when the addition of fiber content goes to 50%, the increase in C_u was up to 20 kPa (around 30 times higher than that of untreated peat). Fig. 2-b presents the results of fiber incorporated MICP. Compared to the fiber alone treatment (Fig. 2-1), fiber incorporated MICP (Fig. 2-b) improved the strength considerably. For example, the late strength (7 days) of peat soil treated by fiber alone (50%) was around 20 kPa, whereas the corresponding fiber incorporated MICP shown an increase up to 42 kPa. However, the increase in the strength is not very significant at lower fiber contents. For example, at 20% fiber content, the fiber alone achieved around 3 kPa, and the increase was up to around 8 kPa in fiber incorporated MICP. This observation could possibly be attributed to the effect of excess moisture content.

Figure 3-a presents the variation of moisture content versus fiber addition. As expected, the increase in fiber addition gradually decreases the moisture content. At the fiber addition of 40%, the moisture content was reached to the value of around 200%, and at the moisture content higher than 200%, there was no significant improvement observed in C_u of the fiber incorporated MICP. This observation is comparable with the previous observation by Cheng et al. [3]. By investigating the MICP under saturation degrees vary between 20-100%, Cheng et al. [3] have found that the saturation higher than 80% had only a little impact on *UCS* and elastic modulus (*E*) of treated coarse sands. It is worth noting that the microfeatures of the precipitated carbonates are significantly influenced by water content, determining the mechanical responses. When the MICP was performed in peat soil at higher moisture contents (above 200%), the carbonates were achieved more as suspension forms in existing moisture, rarely connecting the fibers. On the other hand, further addition of fibers (above 40%) reduce the moisture content and densify the peat soil, leading to the increased connections of fiber elements.

The SEM analysis has demonstrated that the precipitated carbonates have filled the open cellular structure of fibers (Fig. 3-b), coated and connected the fibers (Fig. 3-c), which leads to the increase in both surface roughness of fibers hence shear resistance. The measured precipitated carbonate content was within the range 5-8% (w/w%). This precipitated carbonate content is relatively lower than that obtained in peat soil when treated by hydraulic injection [4]. This could be attributed to the mixing strategy used. In this work, the resources were supplied to soil only at the beginning (initial mixing), whereas multiple injections were possible in hydraulic injection [4]. Therefore, either increasing the initial resource concentration or multiple mixing could be possible ways to increase the precipitation. It is worth mentioning that owing to the impermeable nature of peat, the mixing method is more appropriate compared to the surface injections.

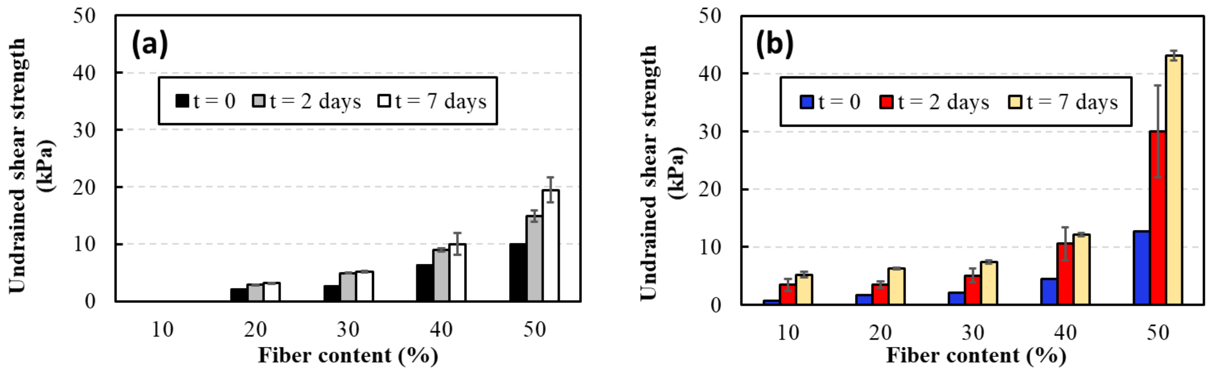

Figure 2: Undrained shear strength of peat treated by (a) fiber alone and (b) fiber incorporated MICP

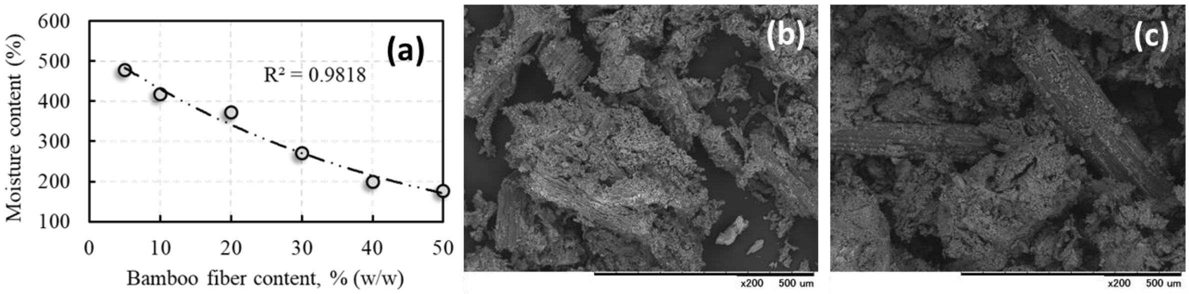

Figure 3: (a) Variation of moisture content versus fiber content, (b-c) SEM images of treated peat soil

Conclusions

This study has demonstrated the feasibility of fiber incorporated MICP over the typical MICP on stabilizing the organic peat soil. However, the improvement in mechanical responses and microfeatures of the precipitated carbonates are significantly influenced by the water content. When the water content above 200%, the carbonates are precipitated as suspension forms, leading to the insufficient increase in shear resistance. Significant increase is achieved when the peat is treated at the moisture content lower than 200%, which is attributed to the increased connections of fibers due to soil densifying during high fiber addition (above 40%). However, to fully assess the feasibility, further amendments in methodology are necessary, which is currently in the consideration for subsequent phase of this work.

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