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MECHANICAL STRENGTH OF PEAT SOIL TREATED BY FIBER INCORPORATED MICROBIAL CEMENTATION

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ABSTRACT

Peat soil is an accumulation of partially decayed vegetation, formed under the condition of nearly permanent water saturation, which makes the high moisture and compressibility as two main features of peat. In recent years, lack of construction lands diverts the attention of researchers to make use of marginal grounds, like peatland, after some improvements. The past decade has witnessed a growing interest towards microbial induced carbonate precipitation (MICP) due to its reliability, wide application and potential contribution to sustainable and green development. There are two primary aims of this study: (i) investigating the feasibility and effectiveness of MICP in peat soil combined with bamboo fiber reinforcement, and (ii) ascertaining the mechanism of bamboo fiber incorporated MICP. Bamboo fiber possesses some unparalleled advantages owing to its fast growth and ability to survive in diverse climates. This study differs from previous researches in the use of native bacteria isolated from the peat soil, while most of them were conducted using exogenous bacteria which might pose a threat regarding adaption and microbial pollution. Different concentration of cementation resources (1-3 mol/L) and proportion of fibers (0-50%) were studied, and each case was well designed. Treated samples were subjected to fall cone test at certain time intervals to estimate the undrained shear strength. The results revealed that the samples with higher fiber content gained higher strength than others did, whereas high initial cementation resources in soil could contribute to the decline of strength. Microscale observations were also performed on treated samples to clarify the mechanism of MICP incorporated with fiber.

Keywords: Microbial induced carbonate precipitation (MICP), Peat soil, Bamboo fiber, Fall cone test, Native bacteria

INTRODUCTION

Peat is a type of soft soil with high content of fibrous organic matters, which is produced by the incomplete decomposition and disintegration of sedges, trees, mosses, and other vegetation growing in wetland and marshes in the anoxic condition [1]. Consequently, it is often referred as problematic soil due to its low shear strength, high compressibility and high water content [2].

Methods to improve peat soils are typically soil replacement, reinforcement to enhance strength and stiffness, stone columns, piles, chemical admixtures etc. [3], [4]. Chemical stabilization like grouting and mixing using cement and lime, which is one of the most preferred methods to improve the soil for the economical reason [3], [4]. In recent years, although known as the most useful artificial material for construction, cement has suffered criticisms related to its contribution to greenhouse gas emission. According to the UNEP annual report of 2010, to produce 1 ton of cement, 1 ton of CO_2 will be released into the environment, which means annually about 7-8% of overall CO_2 emissions are coming from cement industries [5], [6]. There is an increasing concern that some of these traditional methods are being disadvantaged for the harmful environmental effects.

In recent years, a considerable body of literature is springing up around the theme of MICP (microbial induced carbonate precipitation). The MICP is a relatively innovative technique developed via biological processes, in which the production of calcium carbonate bio-cement relies on the performance of microbial urease [3], [7]. Up to now, several studies have confirmed the effectiveness of MICP on the application of removing contaminants from the air and water, preventing liquefaction, reducing compressibility and permeability, improving soil bearing capacity and so on [3], [4], [8]. The application of this technique could to some extent reduce the dependence on cement products whereby it can be an alternative of green development to traditional methods. In this research, another sustainable material is the bamboo. As one type of most common plant fiber material, it has some unparalleled merits due to its fast growth, survivability under diverse climates and excellent engineering properties [9].

This study set out to investigate the usefulness of bamboo fiber combined with MICP in soil improvement: to assess the feasibility and efficiency of MICP on bamboo fiber reinforced peat soil and to reveal the mechanism in the solidification process. For these purposes, ureolytic bacteria isolated from local peat soil were examined before being utilized in solidification tests; different proportion of bamboo fibers were mixed into the peat to clarify the effect on moisture and strength change; the concentration of cementation material was investigated as one of the significant factors governing the effectiveness of MICP. Finally, fiber incorporated microbial cementation experiments were conducted.

MATERIALS AND METHODS

Characteristics of Soil

The distribution of peat lands in Hokkaido, Japan can be observed in Fig. 1. Peat soil used in this research was obtained from Iwamizawa city (43°18'17.9"N 141°40'23.9"E), Hokkaido (Fig. 1), from the depth of 3 m underground. Collected peat samples were then preserved in the sterile containers under the temperature of 4 °C and then subjected to some laboratory examinations. The intrinsic characteristics of peat soil were obtained in the laboratory, shown in Table 1. According to the American Society for Testing and Materials (ASTM) standard [10], the peat soil can generally be categorized as one of the followings: (i) fibrous, (fiber content ≥ 67%), (ii) hemic or semi-fibrous and or (iii) sapric or amorphous (fiber content < 33%). Based on the analysis, the Iwamizawa peat soil was found to be falling under semi-fibrous category.

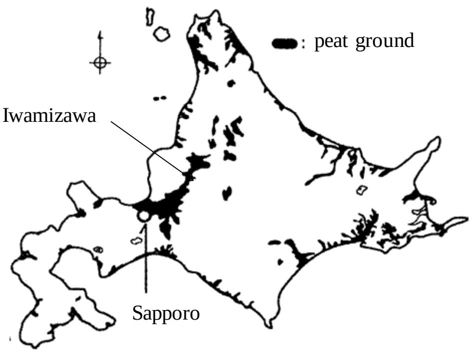


Fig. 1 Distribution of peat ground in Hokkaido [1]

Table 1 Basic characteristics of Iwamizawa peat

Parameters	Values
Water content	711 - 824 %
Density	1.821 g/cm^3
Ignition loss	65.815 %
pH	4.6 - 4.8
k	10^{-4} - 10^{-5} cm/s

Note: Samples were examined from the lower layer to upper layer; k is coefficient of permeability.

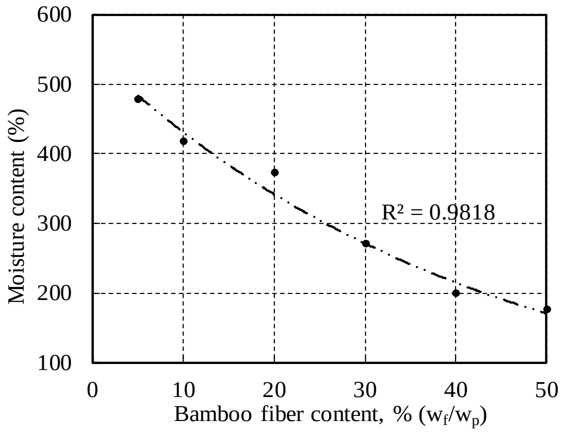


Fig. 2 Variation of moisture absorption with bamboo fiber content

Characteristics of Fiber

The bamboo fiber utilized in this study was made of bamboos with natural moisture content about 26%, with a uniform grain size from 150 to 200 μm. Prior to utilizing the bamboo fiber for solidification test on peat soil, the water absorbing capacity of bamboo fiber was investigated. Totally six cases with bamboo fiber to peat soil ratio at 5%, 10%, 20%, 30%, 40% and 50% were prepared, weighed and dried in the oven at 105°C for more than 48 hours until the mass variation was found to be negligible [11]. The results are shown in Fig. 2, depicting a significant decrease in the water content of peat with increasing fiber content. It is worth noting that the water content could be reduced by half with 20% of fiber addition.

Isolation and Characterization of Bacteria

Isolation of native bacteria

Isolation was conducted by a sequence of dilution (10^1-10^3) of peat soil and then being plated on the NH_4-YE agar medium [12], [13]. After 72 hours of culture at 30°C, colonies were inoculated into new plates using a platinum loop to obtain a purified single colony from groups of distinctive bacteria. Following the purification process, the bacteria were cultured for 24 hours as the preparation of the urease activity test.

Identification of ureolytic bacteria

During the process of urea hydrolysis, the pH of solution increases over time. Urease activity test using cresol-red could realize the identification by a simply qualitative observation on the color change from yellow to purple, indicating an increase in pH from 7.2 to 8.8. Detailed experimental process could be found in the following previous works [12], [13].

The bacteria were added into the testing solution, shaken sufficiently, then incubated at 45℃ for 2 hours. Species changed the color into purple was identified as urease activity positive.

16S rRNA sequencing and analysis

According to the Japanese laws as to the microorganism utilization, it is a must to examine the bio-safety level of bacteria, in case the unknown bacteria would be harmful to human body. Finally, the isolates were characterized by sequencing their 16S rDNA and comparing with the database of Apollon DB-BA 9.0, Gen Bank, DDBJ (DNA bank of Japan) and EMBL (European Molecular Biology Laboratory).

Urease activity and growth curve measurement

Quantitative measurement of bacterial population and urease activity were realized by colorimetry, which is used to test the concentration of a solution by measuring its absorbance of a specific wavelength of light. In case of the determination of bacterial population, the optical density was scanned at the wavelength of 600 nm (OD_{600}). This parameter was set as 630 when measuring the urease activity of bacteria by spectrophotometric determination of ammonia as Indophenol [12], [14].

Treatment and Evaluation

Solidification test

Injection method and mixing method are currently two of the most popular methods for investigating the efficiency of solidification using MICP. In this study, the unique characteristics of peat soil made the choice of mixing method for its reliability and validity. First, $NaCO_3$ was used to adjust the pH condition of peat soil, followed by mixing of cementation resources: $CaCl_2$ (Ca^{2+}), urea (CO_3^{2-}) and ureolytic bacteria (urease). In each 150 g of peat soil, only 15 mL of bacteria (OD_{600}=11, 2-day cultured) were used. Different proportion (10%-50%) of bamboo fibers were added to keep the water content of peat soil at a relatively low level. Sufficient mixing was always followed by adding process. Cases set in this experiment were depicted in the Table 2. Molded samples were then put into an incubator with constant temperature of 30°C for curing. Examinations were carried out after 48 hours and on day 7.

Fall cone test

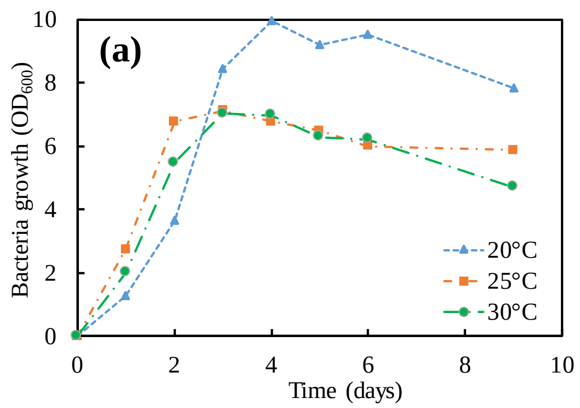
Fall cone test was conducted according to the JGS 0142-2009 [15]. One advantage of this method is that it could be applied on soft clay materials [16]. And for peat, it avoids the problem of the organic matter. The test is based on an approximate relation between the undrained shear strength (τ_f) and the depth of penetration (h), as presented in Eq. 1. K is the fall cone factor which depends mainly on the cone angle, and Q is the cone weight.

$$\tau_f = KQ/h^2 \tag{1}$$

Table 2 Different cases in this experiment

Case		Cementation resources/ V_s	Proportion of fiber (W_f/W_p)
Only MICP	A-1	1 mol/L	None
	A-2	2 mol/L	
	A-3	3 mol/L	
Only fiber	B-1	None	20%
	B-2		30%
	B-3		40%
	B-4		50%
MICP incorporated with fiber	C-1	1 mol/L	20%
	C-2		30%
	C-3		40%
	C-4		50%

Note: V_s is sample volume; W_f is weight of fiber; W_p is weight of peat soil.



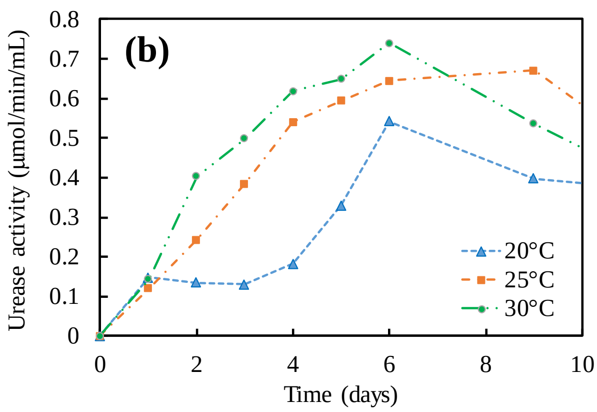


Fig. 3 Performance of PS-1 under different temperatures: (a) growth curve and (b) urease activity

RESULTS

Bacteria Performance

In total, 14 isolated species were tested, of which three species were finally identified as ureolytic bacteria. Two of them were sent to DNA Data Bank and characterized as *Staphylococcus edaphicus* (PS-1) and *Oceanobacillus profundus* (PS-5). After the preliminary analysis, PS-1 was chosen for further experiments as per its higher relative performance, and its performance under different temperature were confirmed by a series of tests. Figure 3 reveals that, for the first few days, there has been a gradual rise in the population of bacteria (showed as OD_{600}), irrespective of the incubation temperature. However, this number reached a peak at the temperature of 20℃ after four days. As per the urease activity tests, the bacteria, on the other hand, showed the highest preference at high temperature. The activity under 30℃ peaked around 0.75 U/mL after 6 days of culturing.

Strength Characteristics

MICP on peat soil (without fiber)

To study the effect of initial concentration of resources, the peat soil was treated preliminary by MICP. As shown in bar chart (Fig. 4), the improvement of peat soil made by MICP seems to be insignificant here, and the development of undrained shear strength declined steadily along with the increase of concentration of cementation material added. Based on the observations, therefore, 1 mol/L was chosen to be appropriate for further experiments.

Fiber incorporated MICP on peat soil

Figure 5(a) presents the experimental data on the strength of fiber reinforced peat soil. The improvement of peat soil with as small as 10% fiber addition was negligible. However, as the fiber content increased to 50%, the shear strength grew by more than 40 times after 7 days of curing under the constant temperature of 30℃. What stands out in Fig. 5(b), which describes the efficiency of MICP incorporated with fiber, is the dramatic growth of undrained shear strength in samples with 50% of fiber, reached 43 kPa, improved by more than 80 times of the untreated, twice of that of fiber reinforced. It also can be clearly seen in this figure that no significant increase in cases with lower fiber content.

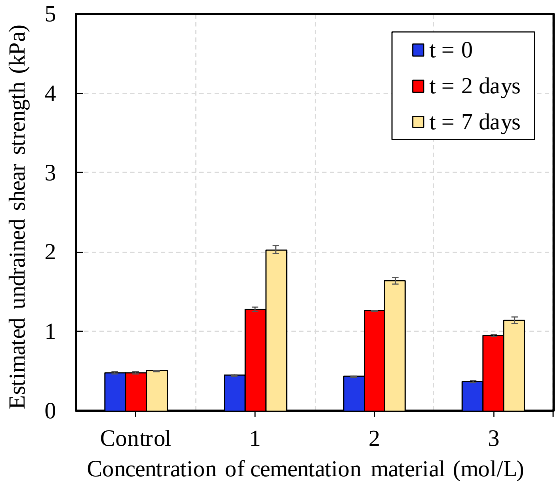


Fig. 4 Effect of different initial concentration of cementation resources

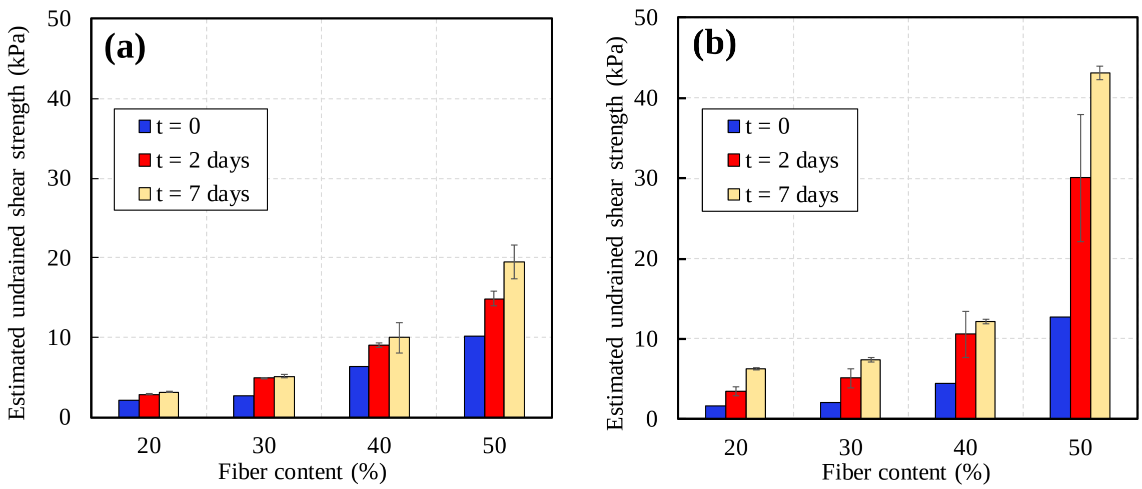


Fig. 5 Fiber incorporated MICP with different concentrations of cementation material:

(a) only fiber and (b) 1 mol/L

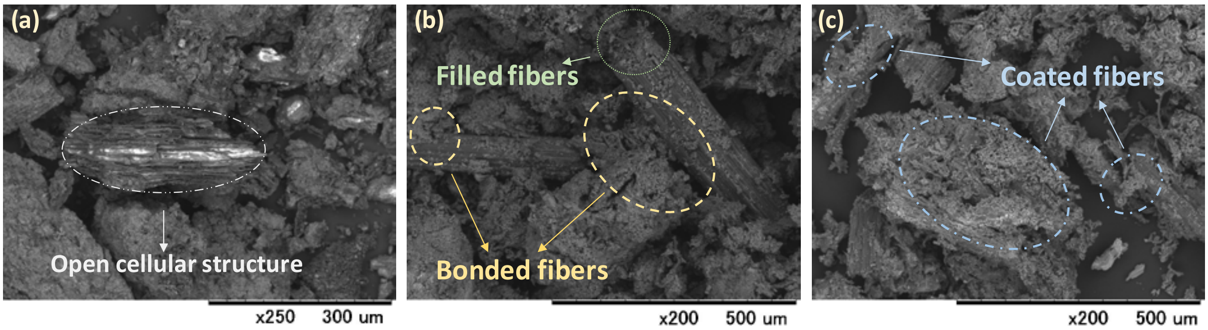


Fig. 6 SEM images of peat soil: (a) untreated; (b-c) MICP- treated

SEM Observation

The results obtained from the SEM (scanning electron microscope) analysis of untreated and treated peat soil are compared in Fig. 6. Fig. 6(a) shows the microstructure of the untreated peat soil. As indicated, fibers were found to be at various sizes and shapes; open cellular structure could also be seen in fibers of untreated soil, suggesting a high degree of decay. When the MICP treatment was applied, the fibers were bonded together by the precipitated calcium carbonate (as depicted in Fig. 6(b)). Certain amount of calcium carbonate was also found to be randomly precipitated on the surface of fibers, which might contribute to the increase in surface roughness. Moreover, the precipitated calcium carbonate tended to crystalline within the open pore structure of the decayed fibers, and a clear microstructure of enhanced fiber material is presented in Fig. 6(c). Overall, the microscopy analysis has provided important insights to understand the mechanism how the strength improvement is achieved in peat soil.

DISCUSSION

Previous studies [17], [18], [19] evaluated the effectiveness of chemical stabilization on peat, of which the results showed that the strength was significantly improved when the considerable amount of pozzolanic materials were mixed *in-situ* or *ex-situ*. Therefore, traditional methods such as Portland cement are firmly being demanded, although some adverse environmental effects are often reported. MICP is a recent call, which is believed to have the potential for stabilizing a wide range of soils. Among the studies performed to this date, only very little were focused on improving peat material, and the improvements were found to be relatively poor [20], which is essentially due to the high moisture content, weak skeleton of peat and intrinsic chemical conditions.

In this study, it has been found that the initial concentration of resources mixed significantly governs the effectiveness of MICP. The results showed that the increasing the initial concentration of resources decrease the strength gaining of peat soil. A possible explanation of this might be that high concentration of MICP chemicals (particularly urea) might affect the urease enzyme. During the experimentation, the softening of peat soil was experienced with the increase in resource concentrations. Basically, peat soil is rich in colloids which are charged nano~micro particles, responsible for most of the chemical responses of peat soil. High concentration of resources would induce the fierce chemical reaction within a short time, leading to the increase in ion-exchange and possibly softening the peat. However, when the moisture is controlled by the fibers, a significant enhancement is achieved in MICP treatment (as compared in Fig. 5).

The query that was not addressed in this study was how this method could alter the consolidation responses of peat soil, which is an important parameter to evaluate. Another limitation may be the limited supply of resources, and multiple mixing phased might further improve the mechanical responses of peat soil. Despite of the possessed limitations, the study suggests the potential value of bamboo fiber in engineering field. Further investigations are necessary to firmly establish the technique with a deeper understanding of the approach.

CONCLUSIONS

The fall cone test, micro-scale observation and a series of examinations were conducted for MICP incorporated with different bamboo fiber ratios, in order to clarify the feasibility and effectiveness of fiber incorporated MICP on peat soil and to ascertain its mechanism. Conclusions could be drawn as below:

(i) The addition of bamboo fiber could greatly reduce the water content of peat soil, resulting in an improvement in strength.

(ii) With the increase of initial concentration of cementation material, the strength gain decreased.
(iii) The undrained shear strength of peat soil was improved by more than 80 times using MICP incorporated with 50% of bamboo fiber, twice as values obtained from cases of fiber only.
(iv) MICP filled the cellular structure, coated and bonded separate fibers together, increasing the roughness of the fiber surface to make them a whole.

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