

EVALUATING MECHANICAL STRENGTH OF PEAT SOIL TREATED BY FIBER INCORPORATED BIO-CEMENTATION

*Meiqi Chen¹, Sivakumar Gowthaman², Kazunori Nakashima² and Satoru Kawasaki²

¹Graduate School of Engineering, Hokkaido University, Japan; ²Faculty of Engineering, Hokkaido University, Japan

*Corresponding Author, Received: 04 June 2020, Revised: 26 Nov. 2020, Accepted: 04 Jan. 2021

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, the lack of construction lands diverts researchers' attention to make use of marginal grounds, like peatland, after some improvements. The past decade has witnessed a growing interest in microbial induced carbonate precipitation (MICP) due to its reliability, broad application, and potential contribution to sustainable and green development. This study has two primary aims: (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 concentrations 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 the fall cone test to estimate the undrained shear strength at certain time intervals. The results revealed that samples with higher fiber content gained higher strength than others did, whereas high initial cementation resources in soil could reduce 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

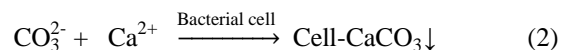
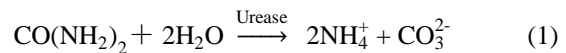
1. INTRODUCTION

Peat is a type of soft soil with a high content of fibrous organic matter produced by the incomplete decomposition and disintegration of sedges, trees, mosses, and other vegetation growing in wetland and marshes [1]. Consequently, it is often referred to as problematic soil due to its low shear strength, high compressibility, and high water content [2]. However, due to the lack of land resources, these marginal lands need to be stabilized to meet increasing demands.

Conventional methods to improve problematic soils, including soil replacement and soil reinforcement using stone columns, piles, and chemical admixtures, are widely applied for different merits [3, 4]. Chemical stabilization like grouting and mixing using cement and lime is one of the most preferred methods to improve the soil for economic reasons [3, 4]. Although Portland cement is known as the most useful artificial material for construction, the cement industry has been criticized for emitting many greenhouse gases in recent years. According to the UNEP 2010 annual report, producing 1 ton of cement emits 1 ton of CO₂ into the environment, accounting for about 7-8% of the total annual CO₂ emissions [5, 6]. Thus, a serious weakness with these methods is the

harmful environmental impact, which has led researchers to seek various approaches as alternatives to these conventional methods.

In recent years, a considerable body of literature is springing up around the theme of MICP (microbial induced carbonate precipitation). 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]. The bacteria origin enzyme catalyzes the hydrolysis of urea into ammonium ions and carbonates Eq. (1), which precipitates in the presence of calcium ions Eq. (2), resulting in connections between soil particles and increasing the shear strength overall [3, 8].



Up to now, many studies have confirmed the effectiveness of MICP on the application of preventing liquefaction, improving soil bearing capacity, removing contaminants from air and water, and so on [3, 4, 8]. This technique's application could reduce the dependence on cement products,

whereby it can be an alternative of green development to conventional methods. In this research, another sustainable material applied is bamboo. As one type of most common plant fiber material, it has some outstanding merits due to its fast growth, survivability under diverse climates, and excellent mechanical properties [9].

This study set out to investigate the usefulness of bamboo fiber combined with MICP in soil improvement: to assess the feasibility and effectiveness of bamboo fiber reinforced MICP on 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. The concentration of cementation materials, as one of the significant factors governing the effectiveness of MICP, was investigated. Furthermore, different proportions of bamboo fibers were mixed into the peat to clarify the effect on moisture and strength improvement. Finally, an in-depth analysis using SEM and XRD was conducted to clarify the mechanism further.

2. MATERIALS AND METHODS

2.1 Characteristics of Soil

The distribution of peatlands 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 sterile containers under the temperature of 4 °C and then subjected to some examinations. The intrinsic characteristics of peat soil were examined in the laboratory, shown in Table 1. According to the American Society for Testing and Materials (ASTM) standard [10], peat soil can be categorized as one of the followings: (i) fibrous, (fiber content ≥ 67%), (ii) semi-fibrous and (iii) sapric (fiber content < 33%). Based on the analysis, the Iwamizawa peat soil was found to be the semi-fibrous type.

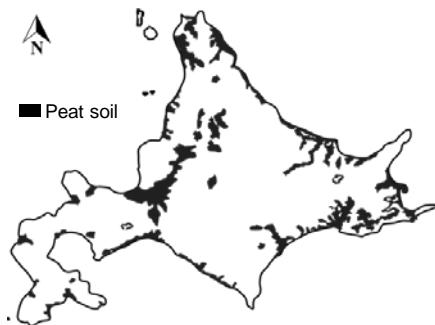


Fig. 1 Distribution of peat ground in Hokkaido [1]

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
<i>k</i>	10 ⁻⁴ - 10 ⁻⁵ cm/s

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

2.2 Characteristics of Bamboo Fiber

The bamboo fiber utilized in this study was made of bamboos with a natural moisture content of about 26%, with a uniform grain size from 50 to 500 μm. Before utilizing the bamboo fiber to stabilize peat soil, the water-absorbing capacity of bamboo fiber was confirmed. Totally six cases with bamboo fiber to peat soil ratio at 5%, 10%, 20%, 30%, 40%, and 50% were prepared 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 shown in Fig. 2 depicted a significant decrease in peat's water content when increasing the fiber addition. It is worth noting that the water content could be reduced by half with 20% of fiber addition.

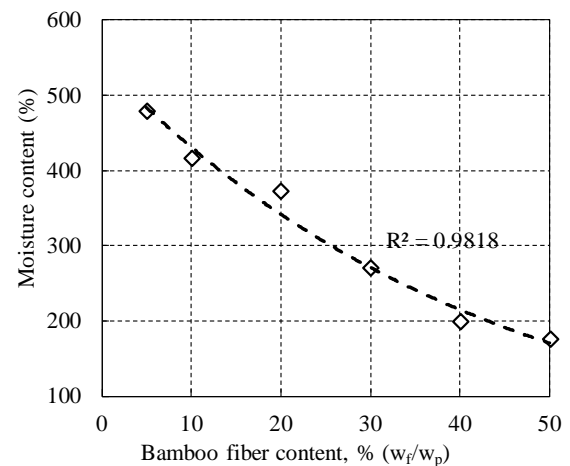


Fig. 2 Variation of moisture absorption with bamboo fiber content

2.3 Isolation and Characterization of Bacteria

2.3.1 Isolation of native bacteria

Peat soil was diluted 10⁻¹-10⁻³ times with sterile distilled water before being plated on the NH₄-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 single purified colony from groups of distinctive bacteria.

Following the purification process, the bacteria were cultured for 24 hours to prepare for the urease activity test.

2.3.2 Identification of ureolytic bacteria

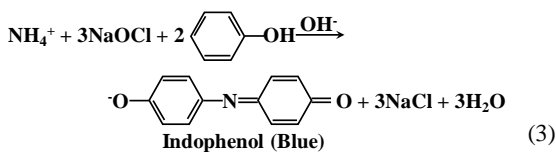
During the process of urea hydrolysis, the pH of the solution increases over time. A simple urease activity test using cresol-red could realize the identification by a qualitative observation on the color change from yellow to purple, indicating an increase in pH from 7.2 to 8.8. Detailed experimental processes could be found in the following previous works [12, 13]. The bacteria were added into the testing solution, shaken sufficiently, then incubated at 45°C for 2 hours. Species changed the color into purple was identified as urease activity positive.

2.3.3 16S rRNA sequencing and analysis

The isolates were characterized by sequencing their 16S rDNA and comparing them with the database of Apollon DB-BA 9.0, Gen Bank, DDBJ (DNA bank of Japan), and EMBL (European Molecular Biology Laboratory). Under Japanese laws as to microorganism utilization, it is a must to examine the bio-safety level of bacteria before applying the microorganism to a field scale. The confirmation of bio-safety level 1 ensures that the species is not toxic to human beings and not an environmental pollutant.

2.3.4 Urease activity and growth curve

Quantitative measurement of bacterial population and urease activity was realized using a spectrophotometer, which tests the concentration of a solution by measuring its absorbance of a specific wavelength of light. In the bacterial population's determination, the optical density was scanned at the wavelength of 600 nm. This parameter was set as 630 nm when measuring the urease activity. The urease activity test in this experiment refers to the Berthelot test, which determines the ammonia as Indophenol (shown in blue). First, one sample is collected from the bacteria-urea solution every 5 minutes and treated with phenol-nitroprusside and sodium hypochlorite. Due to the production of Indophenol, sample color darkens as the concentration increases, as shown in Eq. (3). Finally, the results are quantificationally transferred as the concentration of ammonium ions [12, 14].



2.4 Treatment and Evaluation

2.4.1 Solidification test

The injection and mixing methods are currently two of the most popular methods for investigating the effectiveness of solidification or stabilization by MICP. In this study, peat soil's unique characteristics determined that the mixing method is more reliable than the injection method. As mentioned before, peat soil was acidic soil. To provide a favorable condition for MICP, 1% of NaHCO₃ (by weight) was firstly added to adjust the pH condition of peat soil, followed by the mixing of cementation resources: CaCl₂ (Ca²⁺), urea (CO₃²⁻), and ureolytic bacteria (urease). In each 150 g of peat soil, 15 mL of bacteria (OD₆₀₀=11, 2-day cultured) were added. Different proportions (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 the adding process. Cases set in this experiment were depicted in Table 2. Molded samples were then put into an incubator with a constant temperature of 30°C for curing. Examinations were carried out on day 2 and day 7.

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
	A-2	2 mol/L
	A-3	3 mol/L
Only fiber	B-1	20%
	B-2	30%
	B-3	40%
	B-4	50%
MICP incorporated with fiber	C-1	20%
	C-2	30%
	C-3	40%
	C-4	50%

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

2.4.2 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 to soft clay materials [16]. Moreover, 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. 4. K is the fall cone factor, which depends mainly on the cone angle, and Q is the cone weight.

$$\tau_f = KQ/h^2 \quad (4)$$

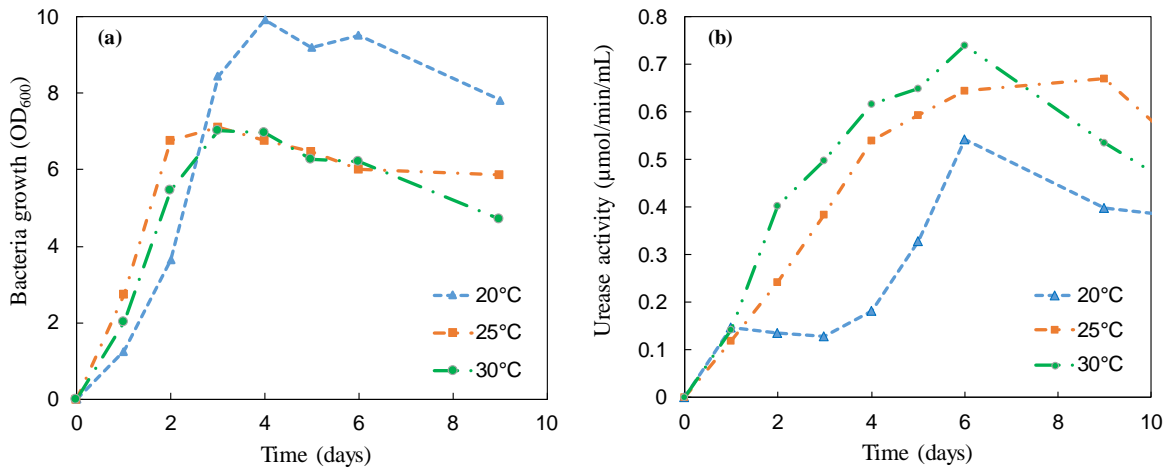


Fig. 3 Performance of PS-1 under different temperatures: (a) growth curve and (b) urease activity

3. RESULTS

3.1 Bacteria Performance

In total, 14 isolated species were tested, of which three species were finally identified as ureolytic bacteria. After the DNA analysis, PS-1 (*Staphylococcus edaphicus*) was chosen for further experiments as per its higher relative performance, and a series of tests confirmed its performance under different temperatures. Figure 3 reveals that, for the first few days, there has been a gradual rise in the population of bacteria (shown as OD₆₀₀), irrespective of the incubation temperature. As per the urease activity tests, the bacteria, on the other hand, showed a higher performance at high temperatures. The activity at 30°C peaked around 0.75 µmol/min/mL.

3.2 Strength Characteristics

3.2.1 MICP on peat soil (without fiber)

To study the effect of the initial concentration of resources, the peat soil was treated preliminary by MICP. As shown in Fig. 4(a), the improvement of peat soil made by MICP was insignificant here, and the development of undrained shear strength declined steadily along with the increase of concentration of cementation material added, which could be explained by their difference in carbonate content shown in Fig 4(b): a high concentration of cementation material inhibits the precipitation of carbonate, thus resulting in a weak strength improvement. Therefore, 1 mol/L was chosen to be appropriate for further experiments.

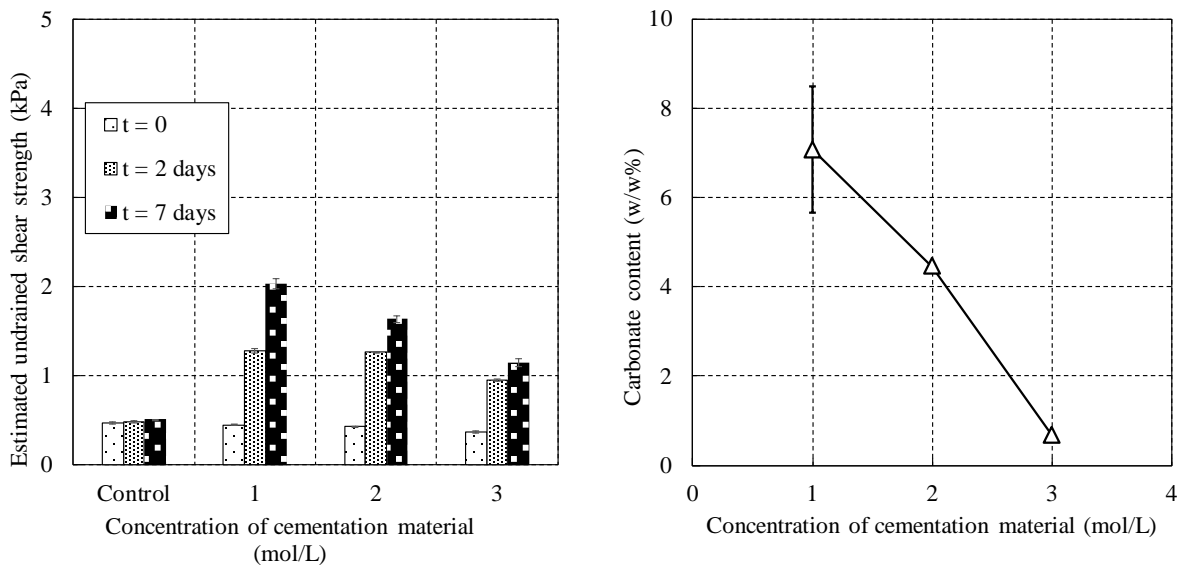


Fig. 4 Effect of different initial concentrations of cementation resources:(a) strength improvement and (b) carbonate content

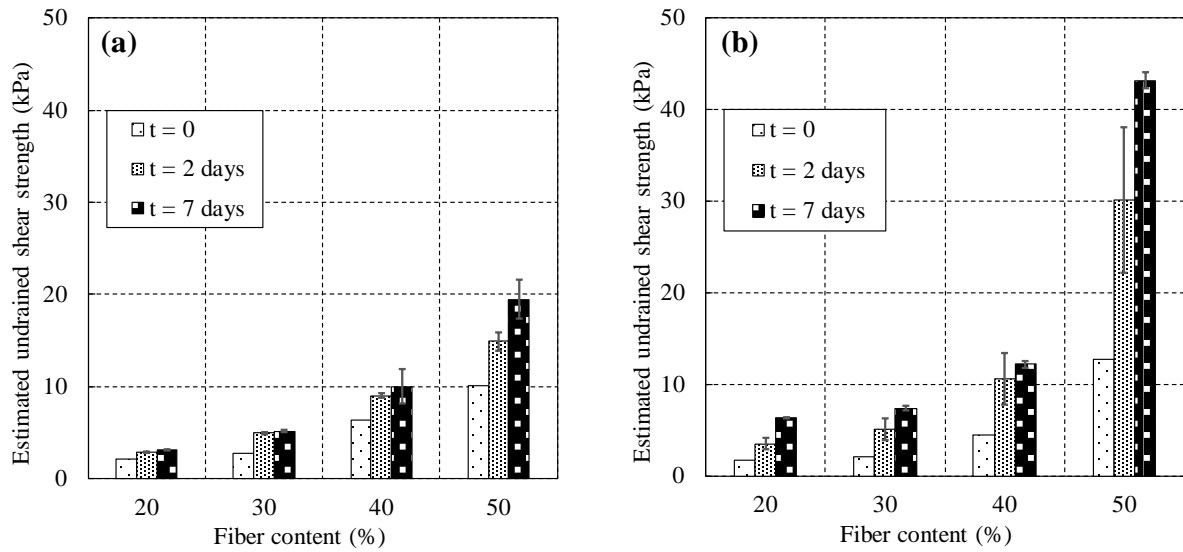


Fig. 5 Fiber incorporated MICP with different concentrations of cementation material: (a) only fiber and (b) 1 mol/L

3.2.2 Fiber incorporated MICP on peat soil

The experimental data of the strength improvement of fiber-reinforced peat soil is presented in Fig. 5, shown above. The improvement of peat soil with fiber addition as small as 10% was negligible. However, as the fiber content increased to 50%, the shear strength grew by more than 40 times after seven days of curing under the constant temperature of 30°C. 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. In contrast to this doubled improvement by MICP, no such significant difference could be found in cases with lower fiber content (10%-40%) when comparing Fig. 5(b) with Fig. 5(a).

3.3 SEM Observation & XRD Analysis

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 of 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)). A 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 an explicit microstructure of enhanced fiber material is presented in Fig. 6(c). Overall, the microscopy analysis has provided important insights to understand the mechanism of how strength improvement is achieved in peat soil.

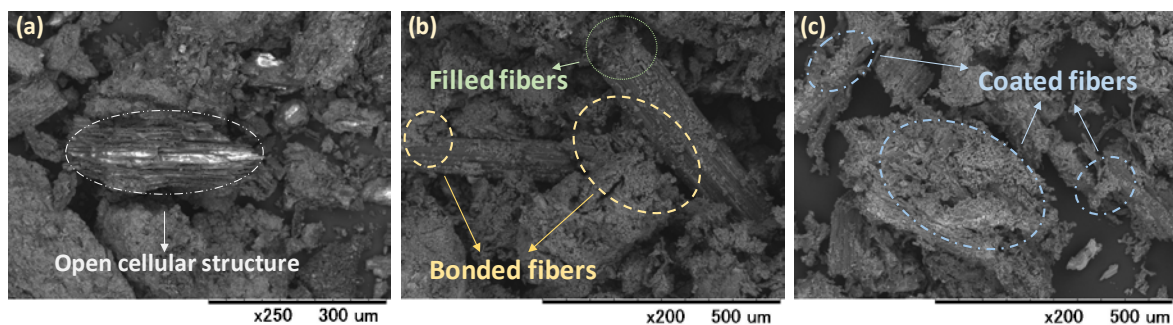


Fig. 6 SEM images of peat soil: (a) untreated; (b-c) MICP- treated

Fig.7 illustrates the result of X-ray diffraction analysis on peat soil treated by MICP. It is apparent from this figure that the primary precipitation in the MICP-treated sample is the calcite. It should be noted that the typical crystal shape of rhombohedral calcite could not be observed in the images obtained from SEM analysis. Relatively smaller calcite crystals are evidenced in micrographs of MICP treated peat matrix compared to that had been observed in MICP treated sands. One possible reason might be the dissolved organic matter; due to its negative charge, it might interact with supplied Ca^{2+} ions and inhibit the growth of calcium carbonate crystals. However, this needs to be evidently addressed in the future works.

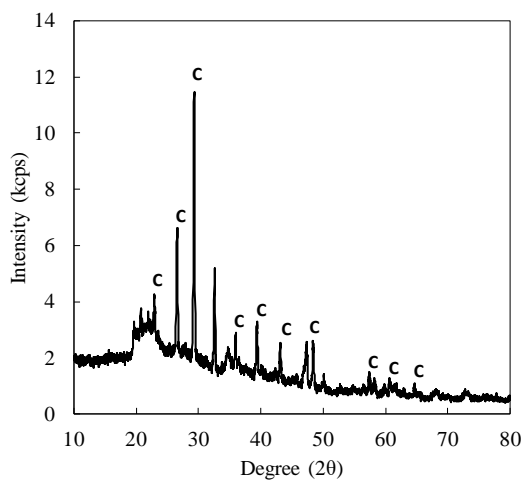


Fig. 7 X-ray diffraction analysis

4. DISCUSSION

Previous studies [17-19] 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 was 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 increasing the initial concentration of resources decreases the strength gaining of peat soil. A possible explanation of this might be that mixing

high concentration of MICP chemicals (i.e. urea and calcium chloride) might denature the urease enzymes and lessen their functionality. Moreover, during the experimentation, the substantial softening of peat soil was also experienced with the increase in resource concentrations. Peat soil is rich in colloids, which are charged nano~microparticles, responsible for most of the chemical responses of peat soil. High concentration of resources would possibly interact with charged colloids, leading to soften the peat. However, when the fibers control the moisture, 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 phases might further improve the mechanical responses of peat soil. Despite the possessed limitations, the study suggests the potential value of bamboo fiber in the engineering field. Further investigations are necessary to firmly establish the technique with a deeper understanding of the approach.

5. CONCLUSIONS

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

- (i) The addition of bamboo fiber could significantly reduce the water content of peat soil, resulting in an improvement in strength.
- (ii) With the increase in the 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.

6. ACKNOWLEDGMENTS

The authors express the gratitude to Civil Engineering Research Institute for Cold Region (Sapporo, Japan) for their fullest supports and technical assistance. This work was partly supported by JSPS KAKENHI Grant Number 19H02229.

7. REFERENCES

- [1] Huat B. B. K., *Organic and Peat Soil Engineering*. 1st ed. University Putra Malaysia Press, Serdang, Malaysia, 2004, pp. 1-15.
- [2] Kazemian S., Huat B. B. K., Prasad A., Barghchi M., A state of the art review of peat: Geotechnical engineering perspective, *Int. J. Phys. Sci.*, Vol. 6, 2011, pp. 1974-1981.
- [3] DeJong J. T., Mortensen B. M., Martinez B. C., Nelson D. C., Bio-mediated soil improvement, *Ecol. Eng.*, Vol. 36, 2010, pp. 197-210.
- [4] Whiffin V. S., van Paassen L. A., Harkes M. P., Microbial carbonate precipitation as a soil improvement technique. *Geomicrobiol. J.*, Vol. 24, 2007, pp. 417-423.
- [5] UNEP Annual Report 2010: United Nations Environment Programme; ISBN 9789280731491, 2011.
- [6] Islam M. T., Chittoori B. C. S., Burbank M., Evaluating the Applicability of Bio-stimulated Calcium Carbonate Precipitation to Stabilize Clayey Soils, *J. Mater. Civ. Eng.*, Vol. 32, 2020, pp. 1-11.
- [7] Portugal C. R. M. e., Fonyo C., Machado C. C., Meganck R., Jarvis T., Microbiologically Induced Calcite Precipitation bio-cementation, green alternative for roads – is this the breakthrough? A critical review, *J. Clean. Prod.*, Vol. 262, 2020, 121372.
- [8] Ivanov V., Chu J., Applications of microorganisms to geotechnical engineering for bio-clogging and bio-cementation of soil in situ. *Rev. Environ. Sci. Biotechnol.*, Vol. 7, 2008, pp. 139-153.
- [9] Gowthaman S., Nakashima K., Kawasaki S., A state-of-the-art review on soil reinforcement technology using natural plant fiber materials: Past findings, present trends, and future directions, *Materials (Basel)*, Vol. 11, 2018, 553.
- [10] ASTM D1997-13: Standard test method for laboratory determination of the fiber content of peat samples by dry mass, ASTM International 2013.
- [11] ASTM D2216-19: Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass.
- [12] Gowthaman S., Iki T., Nakashima K., Ebina K., Kawasaki S., Feasibility study for slope soil stabilization by microbial induced carbonate precipitation (MICP) using indigenous bacteria isolated from cold subarctic region, *SN Appl. Sci.*, Vol. 1, 2019, 1480.
- [13] Gowthaman S., Mitsuyama S., Nakashima K., Komatsu M., Kawasaki S., Biogeotechnical approach for slope soil stabilization using locally isolated bacteria and inexpensive low-grade chemicals: A feasibility study on Hokkaido expressway soil, Japan, *Soils Found.*, Vol. 59, Issue 2, 2019, pp. 484-499.
- [14] Bolleter W. T., Bushman C. J., Tidwell P.W., Spectrophotometric Determination of Ammonia as Indophenol, *Anal. Chem.*, Vol. 33, Issue 4, 1961, pp. 592-594.
- [15] JGS, 2009. Testing Methods and Their Interpretation for Geotechnical Materials (in Japanese).
- [16] Tanaka H., Hirabayashi H., Matsuoka T., Kaneko H., Use of fall cone test as measurement of shear strength for soft clay materials, *Soils Found.*, Vol. 52, Issue 4, 2012, pp. 590-599.
- [17] Kalantari B, Huat B. B. K, Load-bearing Capacity Improvement for Peat Soil. *European Journal of Scientific Research*, Vol. 32, Issue 2, 2009, pp. 252-259.
- [18] Erdem O. Tastan, Tuncer B. Edil, F. ASCE, Craig H. Benson, F. ASCE; and Ahmet H. Aydilek, M. ASCE, Stabilization of Organic Soils with Fly Ash, *J. Geotech. Geoenviron. Eng.*, Vol. 137, Issue 9, 2011, pp. 819-833.
- [19] Hayashi H., Nishimoto S., Strength Characteristic of Stabilized Peat using Different Types of Binders. *International Conference on Deep Mixing Best Practice and Recent Advances*, Sweden, CD-R, Vol. 1, 2005, pp. 55-62.
- [20] Canakci H., Sidik W., Kilic I. H., Bacterial Calcium Carbonate Precipitation in Peat. *Arab J Sci Eng.*, Vol. 40, 2015, pp. 2251-2260.