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# HIGH WATER CONTENT PEAT SOIL IMPROVED BY MICP TECHNIQUE WITH FIBER-REINFORCEMENT

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## ABSTRACT

Peat soil is referred to as problematic soil that uniquely forms under anaerobic and water-saturated conditions. It is usually characterized as organic soil of high compressibility, high water content, and low shear strength. To reduce the environmental impact, instead of using cement products to stabilize it, a relatively novel technique based on the bio-mineralization principle, microbially induced carbonate precipitation (MICP), was adopted to improve the soil matrix. Besides, this study introduced wastepaper fibers from the paper recycling process onto MICP treatment. The objectives were to investigate the effects of fiber reinforcement (0-50% addition) on the undrained shear strength (USS) improvement and contributing factors to the MICP effectiveness. Furthermore, the fiber-reinforced and MICP treated samples were subjected to dispersive crumb tests to examine their stability under a water-logged environment. The results showed a significant improvement in USS up to 360 folds observed when 50% of fibers were introduced onto MICP treatment. The dispersion tests revealed a stable state of MICP treated sample with fiber reinforcement, while the fiber reinforcement alone showed a swelling behavior.

*Keywords: Peat soil, Microbially induced carbonate precipitation (MICP), Wastepaper fiber, Fall cone test, Dispersive crumb test*

## INTRODUCTION

According to the latest report on the global distribution of peatland, peat soil covers approximately 2.84% of the world land area [1]. Formed under extreme conditions of high acidity and waterlogging, this type of soil usually exists at high organic and water levels [2]. Peat deposits possess undesirable engineering properties, so improving this marginal land has been challenging for engineers [3]. For the past several decades, most conventional methods using many cement products have been accused of contributing significantly to $CO_2$ emissions [4]. Nowadays, since we are facing an unprecedented crisis due to global warming, engineers now tend to consider more undesirable consequences that may come with the improvement than before, generating more and more novel technologies of sustainability.

Microbial induced carbonate precipitation (MICP) is one of these techniques, and now it is increasingly described as a green and reliable alternative to conventional methods in many research fields. Unlike conventional techniques, in MICP process, urease produced by living organisms plays a vital role in controlling the reaction rate flexibly. The following equations explain how the bio-mineralization occurs [5, 6]:

$$CO(NH_2)_2 + 2H_2O \xrightarrow{\text{Urease}} 2NH_4^+ + CO_3^{2-} \quad (1)$$

$$CO_3^{2-} + Ca^{2+} \longrightarrow CaCO_3\downarrow \quad (2)$$

This technique has broad application prospects, including soil stabilization, liquefaction prevention, coastal erosion control, fugitive control, etc. [7, 8]. In this study, the focus is concentrated on soil improvement, aiming to enhance one type of high-water content peat soil. The use of wastepaper fibers recycled from a paper mill differs this research from most other reports. Due to its excellent water holding capacity, the wastepaper fiber was expected to stabilize the excessive water in the peat. Globally, the recycling rate of wastepaper fibers keeps at a low level in developing countries. If these wastes could become useful materials in the construction industry, the increasing recovery rate would contribute to sustainable development.

The objectives of this study are i) to investigate the factors that determine the effectiveness of MICP on peat soil; ii) to examine the feasibility of stabilizing high water content peat soil using wastepaper fiber-reinforced MICP technique; iii) to evaluate the performance of the treated soil samples in a water-clogging condition. Strength improvement data were obtained using fall cone test. The effectiveness of MICP was evaluated by the measurement of calcium carbonate content and dispersive crumb test. These experimental works provide a fresh insight into the reuse of waste materials and generate sustainable ideas that combine wastes with novel techniques to achieve a win-win situation.

## MATERIALS AND METHODOLOGY

### Peat Soil

Peat soil samples were collected from Iwamizawa, Hokkaido, Japan. Table 1 presents the basic characteristics of Iwamizawa peat. The distinguishing characteristics between Iwamizawa peat and normal soils are its high water content (around 800%) and pH lower than 5.

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 the upper layer; $k$ is the permeability coefficient.

### Wastepaper Fiber

Wastepaper fibers (WPF) are a mixture of waste materials produced in a paper mill, with cellulose fibers, the basic structural constituent of all plant fibers, and ash content as two dominant components. Meiwa Seishi Genryo Company, Japan, provided the fibers used in this study. The image captured by scanning electron microscopy (SEM) illustrates the appearance of WPF (see Fig. 1 below). Basically, a wide range of fiber lengths from 20 to 500 µm was observed.

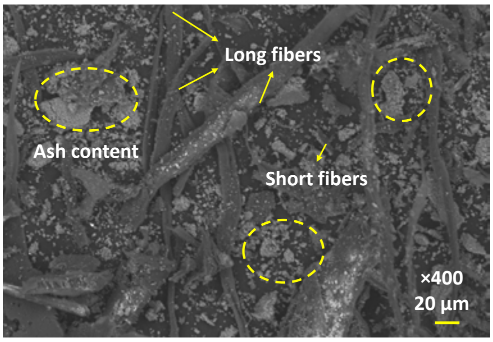

Fig. 1 SEM image of WPF

### Bacteria

The ureolytic bacterium (as a source of urease) used in this study is *Lysinibacillus xylanilyticus*, a gram-positive species with a rod shape (8-10 µm long) which was previously isolated from Hokkaido by Gowthaman et al. [9]. Its urease activity tends to peak at around 3.5 U/mL at a neutral condition (pH 7-8) after 72 hours of cultivation at 25℃ [9]. Since the previous report has corroborated its reliability, the bacterial preparation was done following the same method, using $NH_4$-YE (ATCC 1376) as the culture medium and 25 ℃ as the cultivation temperature.

Table 2 Experimental Cases

| | Category | Conc. of $CaCl_2$ & urea | Fiber addition |
|---|---|---|---|
| Set 1 | Effect of fiber addition | non | 0%<br>10%<br>30%<br>50% |
| Set 2 | Effect of initial pH | pH 4.5<br>pH 7 | non |
| | Effect of conc. of $CaCl_2$ & urea | 1 M<br>2 M<br>3 M | |
| Set 3 | MICP treatment reinforced by fibers | 1 M | 0%<br>10%<br>30%<br>50% |

### Experimental Cases

Cases set in this experiment were depicted in Table 2. In this study, considering the characteristics of peat soil, MICP treatment was conducted by mixing all the materials added in the following order: 0.5% of $CaO_2$, for pH adjustment; WPF at different ratios; $CaCl_2$ & urea; and bacterial culture solutions, with an $OD_{600}$ around 10. It should be mentioned that all the ratios presented in this study refer to proportion by the weight of soil. For each 182 g (100 cm$^3$) of peat soil, 15 mL of bacteria were added. The concentration of cementation materials was calculated based on the volume of soil. Molded samples were sealed and then put into an incubator with a constant temperature of 25°C for curing. Strength examinations were carried out three times: right after the sample preparation, 24 hours, and day 7.

### Evaluations

*Fall cone test*

The fall cone apparatus (release-stop type DH-22NM, cone angle=60°) is provided by Seikensha, Tokyo, Japan. The tests are conducted according to the JGS 0142-2009 [10]. It has been reported that this test could be a feasible and reliable method to estimate the shear strength for soft clay materials. For Iwamizawa peat, this test is a quick way to examine the strength improvement over time. The estimation is based on an approximate relation between the undrained shear strength ($s_u$) and the depth of penetration ($h$), as presented in Eq. 3.

$$s_u = k(mg/h^2) \tag{3}$$

Where fall cone factor $k$=0.29, cone mass $m$=60 g, and earth gravity acceleration $g$=9.81 N/kg.

*Calcium carbonate measurement*

The measurement of calcium carbonate is achieved by using a sealed container equipped with a pressure gauge, which was developed by Fukue et al. [11]. It is based on a simple principle: the pressure inside the container increases due to the carbon dioxide produced by the reaction between calcium carbonate and hydrochloric acid. This change in pressure could be transformed into the mass of calcium carbonate using an established calibration curve. For each test, 2 g of dry samples were taken from the sample and reacted with 20 mL of HCl solution (2 mol/L).

## RESULTS

### Fiber Reinforcement

The first test was carried out to measure the variation in strength with different fiber contents, as shown in Fig. 2. It can be found that the addition of WPF enhanced the USS significantly. When the fiber content was up to 50%, an improvement ratio of 200 folds and a significant reduction of water content were observed. It is considered that the water reduction is responsible for the improvement since the high water content controls the shear strength of Iwamizawa peat.

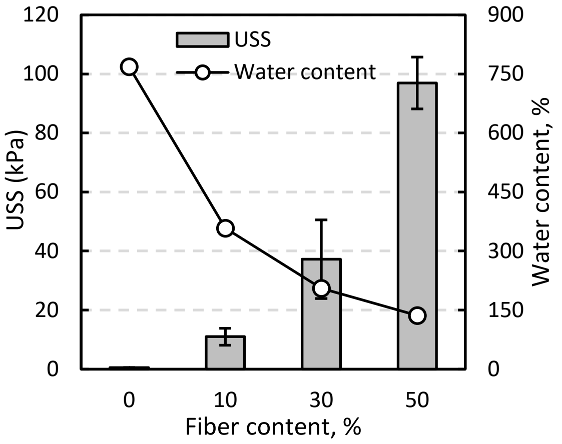

Fig. 2 Effect of fiber addition on undrained shear strength (USS) improvement and the water content

### Contributing Factors of MICP Treatment

*Effect of initial pH*

Having an acidic condition (pH 4.5) makes it quite challenging to improve the peat by MICP treatment because it inhibits the urease activity of bacteria and the precipitation of carbonate. Therefore, to tackle this problem, the acidic peat was adjusted to a neutral condition (around pH 7) by adding 0.5% of $CaO_2$ (agricultural fertilizer). A comparison of the adjusted and unadjusted strength is illustrated in Fig. 3(a), revealing a significant difference in strength improvement. What is striking here is that a doubled improvement ratio when the acidic condition was altered into a neutral one, which indicates a significant enhancement in the effectiveness of MICP.

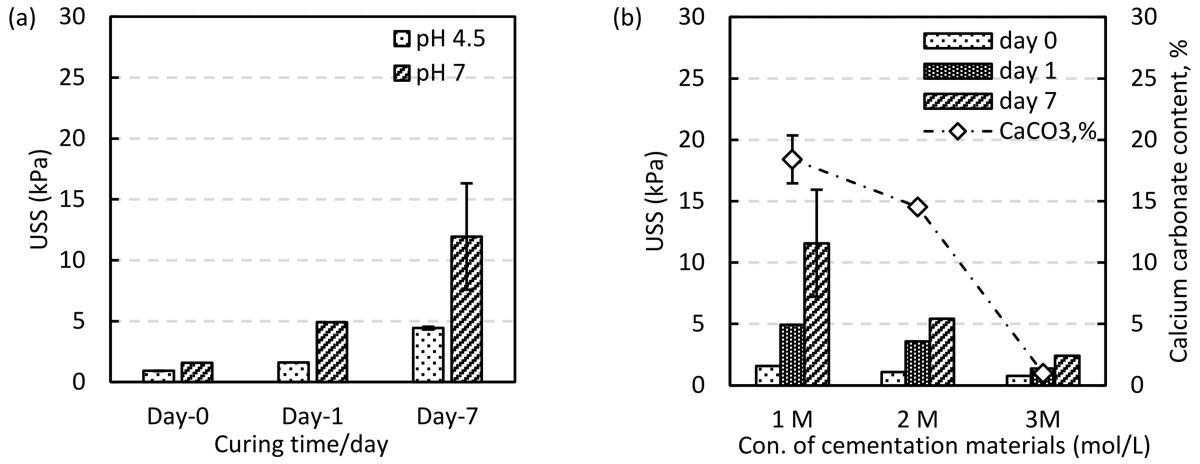

Fig. 3 Contributing factors of MICP: (a) effect of initial pH; (b) effect of concentration of cementation materials

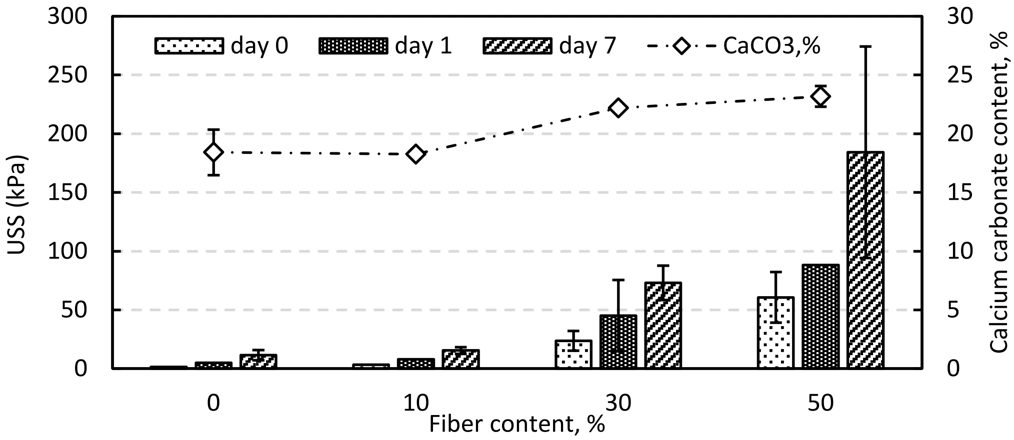

Fig. 4 MICP treatment reinforced by different fiber content (10%, 30%, 50%), with carbonate content shown by the dash-dotted line

### *Concentration of $CaCl_2$ & urea*

To investigate the effect of different concentrations of cementation materials, a set of MICP treated samples with 1 mol/L, 2 mol/L and 3 mol/L of $CaCl_2$ & urea were prepared. From the bar chart in Fig. 3(b), it can be seen that samples with a higher concentration appeared to be less improved by the treatment. Strong evidence was found in the results of calcium carbonate content. The 1 M case yielded a calcium carbonate precipitation of 18%, while only 1% of precipitation was obtained in the 3 M case. The concentration of 1 mol/L was the optimum among three cases, with an improvement ratio of more than 20 times.

## Fiber Reinforced MICP Treatment

Figure 4 illustrates the enhanced strength by WPF (10%, 30%, 50%) reinforced MICP treatment during 7-day curing. It is apparent from this figure that a small amount of fiber addition did not enhance the effectiveness of MICP, which can be explained by the similar calcium carbonate precipitation obtained from 0% case and 10% case. However, when the addition was up to 30%, one-week strength increased by six folds compared to the 0% case. What stands out in this figure is that 50% of fiber addition contributed an improvement ratio of 15 times. Meanwhile, the calcium carbonate content was increased by 25% compared to the 0% case.

The enhancement observed in this figure can be compared with the results shown in Fig. 2. As mentioned before, fibers enhanced the strength significantly by holding the water. Incorporated with MICP treatment, a nearly doubled enhancement was obtained in cases with high fiber content.

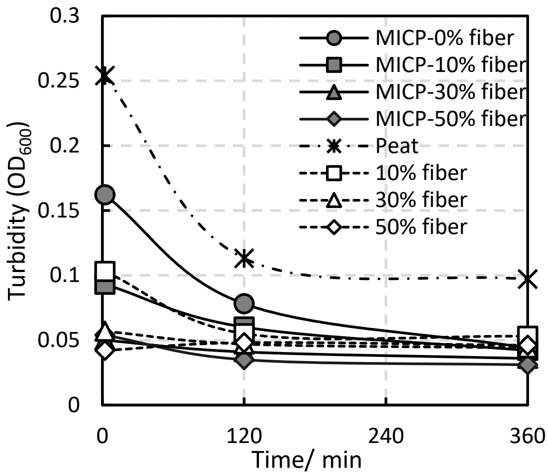

Fig. 5 Turbidity-time curve in crumb tests conducted on untreated peat, fiber-reinforced samples, and fiber-MICP treated samples

## Dispersive Crumb Test

Since the peat was formed in conditions with excessive water, investigating how the stabilized peat performs under water-clogging is essential. Therefore, both untreated and treated peat samples were subjected to crumb tests. The results were presented both in pictures and statistics. As shown in Fig. 5, the quantified turbidity of treated samples verified the remarkable improvement in dispersive properties. Pictures in Fig. 6 illustrate the samples kept in a water-logging condition after 6 hours. High water content peat collapsed immediately when samples were subjected to water immersion (Fig. 6(a)). It is evident from Fig. 6(b-h) that samples became more stable with the increasing fiber addition, with less crumbled material observed at the bottom of the beaker. Remarkably, almost no crumb was found in the MICP case with 50% of fiber addition. It is worth noting here that the fiber-reinforced samples exhibited a swelling behavior during the 7-day curing period, as shown in Fig. 6(c), which accelerated the damaging process when soaking into water. Closer observation on the crumb settled at the bottom of the beaker suggests that fiber-reinforced MICP treated samples are more stable in water for the reason that suspended particles in peat were connected by the bio-cementation.

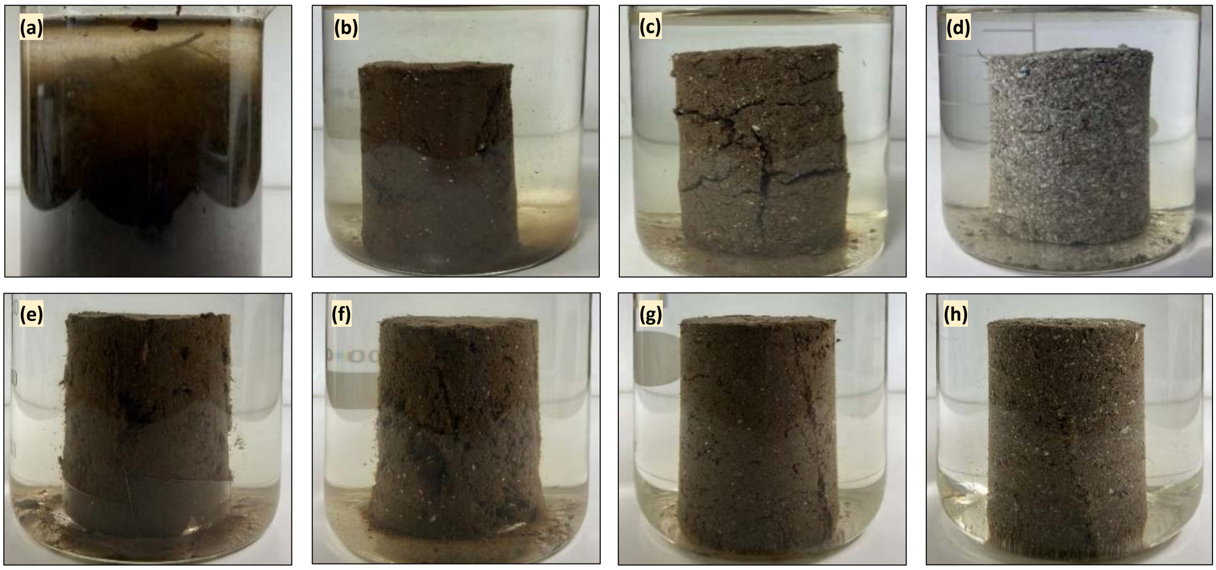

Fig. 6 Demolded samples in a water-clogging state with a 6-hour duration: (a) untreated peat soil; (b) 10%, (c) 30%, and (d) 50% of fiber-reinforced peat; (e) MICP treated sample (1 mol/L); (f) MICP treatment reinforced by 10%, (g) 30% and (h) 50% of fibers

## DISCUSSION

A previous experimental study on improving Iwamizawa peat combined bamboo fibers and MICP treatment [12]. Due to the limited urease activity of the native bacteria, the treated soil remained weak. Overall, it has been confirmed that fiber materials could stabilize high water content soil, which further aids the MICP treatment.

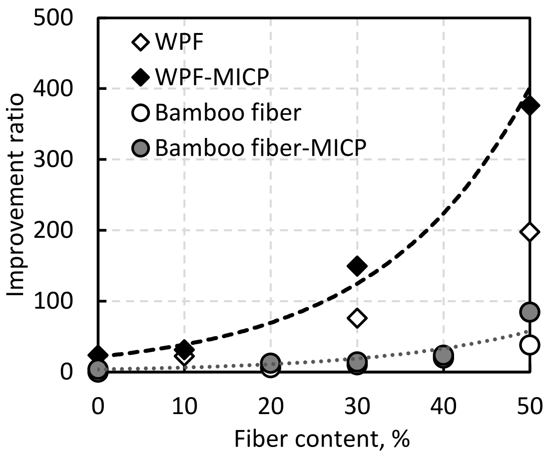

Fig. 7 Improvement ratio by fibers and fiber-MICP [12]

Similarly, in this study, bacteria of higher urease activity and fibers (finer) with a larger specific surface area were used to enhance the strength further. What stands out in this study is that the improvement ratio by wastepaper fibers was more than 5-fold as that by bamboo fibers when the addition was up to 50%. It can be explained by their difference in the capacity of moisture reduction. Compared to bamboo fibers, wastepaper fibers possess a larger specific surface area, thus holding more water, which leads to a significant enhancement in the shear strength.

The results of the dispersive crumb test illuminate a significant improvement in peat soil's stability. As generally known, cellulose fibers hold water and expand, which explains why a relatively poor performance was observed in fiber-reinforced samples. However, it seems that fiber-reinforced MICP treatment could overcome this obstacle since the precipitation functions as a cementitious material that binds the loose fibers.

Considering the organic matter, mainly humic substances in the peat soil, the addition of $CaO_2$ might have affected the solubility of some substances since the pH condition was greatly altered. Furthermore, when mixing the calcium carbonate and urea, there is a severe fluctuation in temperature. Both these chemical and physical changes disturbed the original structure of the soil, which might inhibit the MICP to some extent. As reported in the previous study, the humic substances are of great cation exchange capacity (particularly humic acids), which could be the most challenging part of MICP treatment considering the indispensable role of calcium ions [12]. In soil humus science, these substances, unfortunately, are remained elusive to scientists. Therefore, to obtain a deeper understanding of these substances' role in the MICP process, more efforts need to be made.

## CONCLUSIONS

The present study was designed to investigate the effect of fiber-reinforcement on high water content peat improvement, two contributing factors of MICP treatment on peat, and evaluate the effectiveness of fiber-reinforced MICP treatment. The first set of experiments conducted in this research has identified a remarkable enhancement in soil strength when reinforced by wastepaper fibers. The second set confirmed a favorable condition for effective MICP treatment. The results of the third set revealed a doubled improvement in shear strength when fiber reinforcement was combined with MICP treatment, followed by dispersive crumb test, which indicates an essential finding of the treated samples' stability. A discussion of samples' durability lies beyond the scope of this study, which is recommended for future work.

In general, this study suggests an essential role for wastepaper fibers in amending high water content peat and highlights the feasibility of MICP treatment on soil improvement.

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