Bio-mediated improvement process in a reinforced soil with waste paper fiber

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ABSTRACT

The effectiveness of using some natural and/or synthetic fibers such as bamboo, jute, steel fibers, polyester fibers, etc. in the soil improvement techniques has been recognized by many researchers. In addition, eco-friendly soil improvement techniques using biomineralization by microorganisms have attracted attention in recent years. This technique improves the mechanical properties of soil by precipitating calcium carbonate between soil particles and adhering the particles. In the current study, the author investigated an effectiveness of using waste paper fiber to suppress liquefaction and a self-healing process based biomineralization by microorganisms. As a result of solidification tests based on column approach, it was revealed that many calcium carbonate minerals are generated on the surface of waste paper fibers and between sand particles, and uniaxial strength is improved.

Keywords: waste paper fiber, biomineralization, MICP, soil improvement

1 INTRODUCTION

It has been recognized that some natural and/or synthetic fibers such as bamboo, jute, barley straw, steel fibers, polyester fibers, etc. are effective as additives for soil improvement techniques (Hejazi et al., 2012; Dos Santos, et al., 2010). In the soil improvement, the fibers are mixed randomly in soil, and natural fibers are cheap as compared to synthetic fibers and have less harmful effects on natural environment (Kumar and Mir, 2019).

Under these circumstances, a recycling system by using waste paper fiber (WPF) have attracted attention as additive materials in order to reduce water content of mud soil (Mori et al., 2003). In this system, both a decrease in water content and an increase in shear strength of mud soil can be expected because WPF absorb much of pore water in complex entangling with the soil particles. It is, however, possible that WPF deteriorates in soil over time because the WPF is derived natural cellulose as a main ingredient. Hence, it is doubtful whether WPF will be able to play its role through all eternity in actual environment.

On the other hand, bio-mediated soil improvement techniques such as Microbially Induced Carbonate Precipitation (MICP) (Zhu and Dittrich, 2016), which involves microorganisms such as ureolytic bacteria have received substantial research attention (Danjo and Kawasaki, 2016; DeJong et al., 2006). This technique improves the mechanical properties in soil by precipitating calcium carbonate between soil particles, and adhering the particles (Matsubara and Yamada, 2020; DeJong et al., 2010). Also, this technique is considered as one of the eco-friendly soil improvement techniques because MICP phenomena are also observed in a natural environment (Oshiro and Matsubara, 2018; Sakiyama and Matsubara, 2018; Danjo and Kawasaki, 2016).

In the current study, the author attempts to apply the MICP technique using ureolytic bacteria to WPF reinforced soil in order to prevent the degradation of the WPF in the soil. This paper shows some experimental results of column tests and discusses its effects and structural features.

2 MICP BY UREA HYDROLYSIS REACTION

A bio-mediated soil improvement technique refers to a chemical reaction system through biological activity where byproducts of metabolic reactions bring improvement of the engineering properties of soil (DeJong et al., 2010). A majority of the studies on bio-mediated soil improvement using MICP, especially in solidification of soil are based on urea hydrolysis reaction (Zhu and Dittrich, 2016). MICP by the urea hydrolysis reaction is described by the following equations (Matsubara and Yamada, 2020).

\[\text{COO(NH}_2\text{)}_2 + \text{H}_2\text{O} \rightleftharpoons \text{CO}_3^{2-} + 2\text{NH}_3 \]  
\[\text{Ca}^{2+} + \text{CO}_3^{2-} \rightleftharpoons \text{CaCO}_3 \downarrow \]  

Eq. (1) denotes the urea hydrolysis reaction due to metabolism of ureolytic bacteria and Eq. (2) is a chemical reaction describing the precipitation of calcium carbonate. The calcium carbonate precipitation occurs because of microbial metabolic activity that raises the pH around the habitat environment. Also, the increase of local pH may be related to the production of
ammonia resulting from the urea hydrolysis reaction. These bio-alkalization phenomena brings/induces the calcium carbonate precipitation. In the current study, ureolytic bacteria was selected in order to confirm the validity of MICP in the WPF mixed sand.

3 MATERIALS AND METHODS

3.1 Materials

In the current study, WPF of 3 wt% was mixed into a specific sand called as Toyoura sand, a typical clean sand found in Japan (Zhang and Ye, 2013). Fig. 1 shows the appearance of WPF and its microscopic structure captured by Scanning Electron Microscope (SEM). The WPF has a fibrous microscopic structure that are intricately intertwined, and it looks like cotton in macro-scale. Also, the length of fiber is distributed in the range of approximately 120 – 500 μm, and the width is distributed approximately 10 – 40 μm as shown in Fig. 2. It is noted that a mortar mixer, for example, should be used in order to keep from material separation when the WPF is mixed with Toyoura sand. Hereinafter, this mixed sand is called as WPF mixed sand in the paper.

With respect to ureolytic bacteria, Sporosarcina pasteurii (ATCC® 11859™), an alkalophilic soil bacterium with a highly active urease enzyme (Ferris et al., 1996), is used in the current study.

3.2 Laboratory tests and the evaluation method

The column cementation tests were conducted under two test conditions in order to understand the difference of cementation process between Toyoura sand and WPF mixed sand by urea hydrolysis reaction. The schematic diagram of the column test is shown in Fig. 3. The sand samples are set into the center column, and then sterilized ion exchange water is injected into the column from the bottom as shown in Fig. 3. After the sample becomes totally saturated condition by the ion exchange water, ureolytic bacteria and nutrients are injected into the column. In the tests, 300 ml of ureolytic bacteria together with the culture solution were injected only once at the beginning of the tests. Also, 1200 ml of the nutrients where the nutrient composition is as shown in Table 1 were provided from the bottom of the columns every 12 hours.

In this study, the coefficient of hydraulic conductivity can be directly measured by using the inflow column of nutrients and ureolytic bacteria. Hence, in the current study, temporal changes of the coefficient of hydraulic conductivity, pH value, and uniaxial compressive strength (UCS) were selected as evaluate parameters of bio-cementation. With respect to UCS, the strength was predicted based on the results of the needle penetration test. This test is one of the most available methods for measuring the hardness of soft rocks, and the needle penetration gradient is well correlated with the uniaxial compressive strength based on field and laboratory evidences (Ulusay and Erguler, 2012). The UCS (kN/m²) can be obtained from the following equation:

$$\log UCS = 0.987 \log (F/D) + 2.621$$

(3)

Table 1. Nutrient composition.

| Nutrients                      | Addition                     |
|-------------------------------|------------------------------|
| Urea: CO(NH₂)₂                | 0.2 mole (=22.2 g)          |
| Calcium chloride: CaCl₂       | 0.2 mole (=12.01 g)         |
| Ammonium chloride: NaHCO₃     | 10 g                         |

![Fig. 1. Waste paper fiber (WPF). (a): Macroscopic structure, (b): Microscopic structure (SEM image).](image1)

![Fig. 2. Distribution of length and width of waste paper fiber. (a): Length distribution, (b): width distribution.](image2)

![Fig. 3. Schematic diagram of the column test also served as falling head permeability test.](image3)
where \( F \) is the penetration load (N) and \( D \) is the depth of penetration (mm).

Also, microscopic observations were conducted using a SEM to discern the structural difference between Toyoura sand and WPF mixed sand.

4 RESULTS AND DISCUSSION

Fig. 4 shows the state of the test specimens of Toyoura sand and WPF mixed sand after elapsed 48 h and 144 h. In the case of Toyoura sand, although the initial shape of cylinder could not be kept at an initial stage, it was cemented after 144 h. On the other hand, in the case of WPF mixed sand, the shape kept comparatively at even an initial stage, and the specimen was cemented at the elapsed time of 144 h. Although the samples appeared to be well solidified inside the hard-plastic columns (acrylic tube pipes) in the experiments, the broken samples can be observed even after MICP treatment in Fig. 4. This is because of that some parts of the samples were broken when the samples were forcibly removed from the column. Also, the samples would be more solidified if rich nutrition for a long time were provided.

Fig. 5 shows the microscopic structures of Toyoura sand and WPF mixed sand. It is observed from this figure that the microstructure of WPF mixed sand is quite different from that of Toyoura sand. Concretely, WPF is located on and between sand particles and is complicatedly entangled with particles. Hence, it is considered that this complicated entangling structure of WPF mixed sand brings an improvement of cohesion of the sand, which brought the shape stabilization of the specimen at even an initial stage as a result. In addition, MICP technique should be appropriate for the WPF mixed sand because the cementation was also observed in the WPF mixed sand.

Changes in the pH value in each sand with elapsed time are shown in Fig. 6. In each case, although the values increased from 6.8 to 8.3 at an initial stage, the value decreased to approximately 7.6 and stabilized. Based on Eq. (1), it is considered that the initial increasing of pH value is due to the activation of urea hydrolysis reaction with rapid increase of ureolytic bacteria in the column. Also, the number of bacteria is considered to toward to stabilize after elapsed 12 h.

Fig. 7 shows changes in the coefficient of hydraulic conductivity with elapsed time. It is observed from this figure that the coefficient of hydraulic conductivity of the samples decreased with elapsed time, on the other hand, the values are stabilized after elapsed 12 h in each case. Also, the value of WPF mixed sand is larger than that of Toyoura sand, which means that WPF plays the role of a water path and prevents a decrease in permeability due to its water absorption function.

Fig. 8 shows changes in the UCS with elapsed time. UCS in the case of Toyoura sand increased linearly. On the other hand, it is interested that UCS in the case of WPF mixed sand did not appear until elapsed 96 h, but significantly increased at elapsed 144 h.
Changes in the microscopic structures with elapsed time in the case of Toyoura sand and WPF mixed sand are shown in Figs. 9 and 10, respectively. It is observed from Fig. 9 that calcium carbonate is sparsely precipitated on the surface of sand particles at an initial stage (Figs. 9(a), (b)). Subsequently, the amount of calcium carbonate increases on the surface and in the gap of sand particles (Figs. 9(c), (d)). Hence, it is clear that the increasing of strength in the case of Toyoura sand brings from that the discrete sand particles are adhered by the calcium carbonate.

In contrast, it is observed from Fig. 10 that calcium carbonate is locally precipitated on/in WPF at an initial stage (Figs. 10(a), (b)). Subsequently, the amount of calcium carbonate increases on/in WPF and in the gap of sand (Figs. 10(c), (d)). Therefore, it is considered that the increasing of strength in the case of WPF mixed sand brings from that the discrete sand particles are adhered by calcium carbonate precipitated on/in the WPF. That is, the UCS does not increase at an initial stage as shown in Fig. 8 because calcium carbonate precipitates only on/in the WPF. Subsequently, the precipitation covers the WPF over time and ultimately plays the role as a bridging material between discrete particles.

The covering phenomenon shown in Figs. 10(c), (d) makes it appear as if the WPF is wearing armor, which can be considered to delay the degradation of WPF in soil. Figs. 11 and 12 show conceptual illustrations of this precipitation for Toyoura sand and WPF mixed sand, respectively. Although the reason why calcium carbonate precipitations are concentrated around the WPF may be related to the optimal habitat environment of ureolytic bacteria, no specific evidence had been obtained in the current study. However, it is naturally

Fig. 8. Relationship between elapsed time and the uniaxial compression strength by using the needle penetration test.

Fig. 9. Microscopic structures of Toyoura sand with MICP treatment. (a): Initial, (b): 48 h, (c): 96 h, (d): 144 h.

Fig. 10. Microscopic structures of WPF mixed sand with MICP treatment. (a): Initial, (b): 48 h, (c): 96 h, (d): 144 h.

Fig. 11. Schematic diagram for the MICP process in Toyoura sand. The reaction proceeds from (a) to (d).

Fig. 12. Schematic diagram for the MICP process in WPF mixed sand. The reaction proceeds from (a) to (d).
considered that the advantage of traditional MICP technique in sandy soil such as Toyoura sand as a self-organizing soil improvement technique is not lost because the calcium carbonate precipitation on/in WPF and in the gap of sand is expected to continue in the soil. Therefore, the MICP would be useful as a technology to strengthen the soil structure while suppressing WPF weathering in soil.

5 CONCLUSIONS

The current study tried to apply the MICP technique using ureolytic bacteria to the WPF reinforced soil. The laboratory-based experimental results are summarized as follows:

1. The complicated entangling structure of WPF mixed sand brings an improvement of cohesion of the sand, and the cementation by MICP was also observed in the WPF mixed sand.
2. The temporal changes of pH value of WPF mixed sand is equivalent to that of Toyoura sand.
3. The coefficient of hydraulic conductivity of WPF mixed sand is larger than that of Toyoura sand.
4. The UCS of WPF mixed sand appears slightly later than that of Toyoura sand because calcium carbonate precipitation occurs around WPF at initial stage in the WPF mixed sand.
5. The deterioration issues of WPF in the soil may be solved by applying the MICP technique to the WPF mixed soil.

With respect to WPF mixed sand with MICP, there remains some issues to be solved, such as an influence of soil type, long-term sustainability, applicability to actual environment, etc., which are future works as we should attempt to solve.

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