# Development of simple and environmentally friendly soil solidification technique

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## ABSTRACT

We developed and studied a simple and environmentally friendly soil solidification technique utilizing bio-mineralization or bio-cementation process. The microorganism used for this technique was baker's dry yeast. To adjust the pH of the soil and promote mineralization, agricultural fertilizer was used. Sandy soil was solidified by mixing the materials, adding water, and letting them cure. In terms of reproducible results, it was possible to produce solidified bodies with the same strength as cement-improved soil. In our study, only environmentally friendly materials have been used. Therefore, this technique can be applied not only for ground improvement, but also for other various applications such as sandy soil utilization.

**Keywords:** bio-mineralization, soil solidification, ground improvement, environmentally friendly technique

## 1 INTRODUCTION

For ground improvement, using a cement-based solidifying material is a common method. However, using cement has large environmental impacts such as hexavalent chromium contamination and high pH levels. Consequently, there is a risk that the land utilization will be limited after the application of cement. An environmentally friendly alternative process has been developed called bio-mineralization or bio-cementation that uses a microbial reaction to strengthen a material (DeJong et al., 2006; Whiffin et al., 2007; Ivanov and Chu, 2008; Inagaki et al., 2011; Akiyama and Kawasaki, 2012; Martin et al., 2013; Kawasaki, 2015; Danjo and Kawasaki, 2016). Ureolytic bacteria, such as *Sporosarcina pasteurii*, in particular, have been used in bio-mineralization. Ureolytic bacteria are effective in the strength development of a solidified body by creating an alkalescent environment that is advantageous for mineralization. However, there are significant problems for its practical use in the environment, such as that ureolysis generates ammonia, releasing bad odor in the surrounding environment, and contributes to nitrogen contamination of the land.

To develop a practical technique that can be applied in the environment, we studied a simple and environmentally friendly soil solidification technique. The microorganism used for this technique was baker's dry yeast. Dry yeast is commonly used and is easy to handle even if the users are not microbiologists. Although dry yeast has previously been used for bio-mineralization (Kawasaki et al., 2006), a satisfactory way to adjust the pH to promote mineralization was not found. In this study, in order to adjust the pH of the soil and promote mineralization, agricultural fertilizer was used. Sandy soil was solidified by mixing the materials, adding water, and letting them cure. In terms of reproducible results, it was possible to produce solidified bodies with the same strength as cement-improved soil. In our study, no materials that have a harmful effect on the environment were used. Therefore, this technique can be used not only for ground improvement, but also for other various applications such as sandy soil utilization. For instance, agricultural land utilization is conceivable by adding appropriately nutrient salts to fertilize and lightly solidify sandy soil.

In this report, we introduce the basic principles of our soil solidification technique and describe the experimental results of this technique intended for use in different applications.

## 2 MATERIALS AND METHODS

### 2.1 Materials

To induce bio-mineralization, dry yeast and compost were used. Dry yeast produced by Oriental Yeast Co., Ltd. (Fig. 1(a)), a commercially available compost made from leaf mold containing *Bacillus* bacteria (Fig. 1(b)), and mountain sand (Fig. 1(c)) were used. MINEKARU (Fig.1(d)) and KEIKARU (Fig. 1(e)) steel slag were used as the agricultural fertilizer (products of TETSUGEN CORPORATION) for pH control of the specimens.

### 2.2 Solidification experiment

Table 1 shows the composition of the materials. The amount of slag fertilizer was adjusted to achieve a pH of 8.0. Mountain sand and slag fertilizers were dried in a drying oven at 110 °C to an absolutely dry state. All materials were mixed in a stainless steel bowl (Fig. 1(f)), then the mixed materials were spread over a stainless steel tray. 1,000 mL of tap water was poured over 3,000 g of mixed materials to produce the specimens. The specimens were cured at a constant temperature of 30 °C in a humidity chamber adjusted to a humidity of 60% for 14 days (Fig. 1(g)).

The mechanisms of the soil solidification were as follows. Carbon dioxide gas was generated by the metabolism of microorganisms (1). The formation of an alkalescent environment with slag fertilizer promoted mineralization and produced carbonates (2), resulting in the solidification of the sand.

Reaction formula:

$$C_6H_{12}O_6 + O_2 \rightarrow 6CO_2 + 6H_2O \quad (1)$$

$$Ca(NO_3)_2 + CO_2 + H_2O \rightarrow CaCO_3 + 2HNO_3 \quad (2)$$

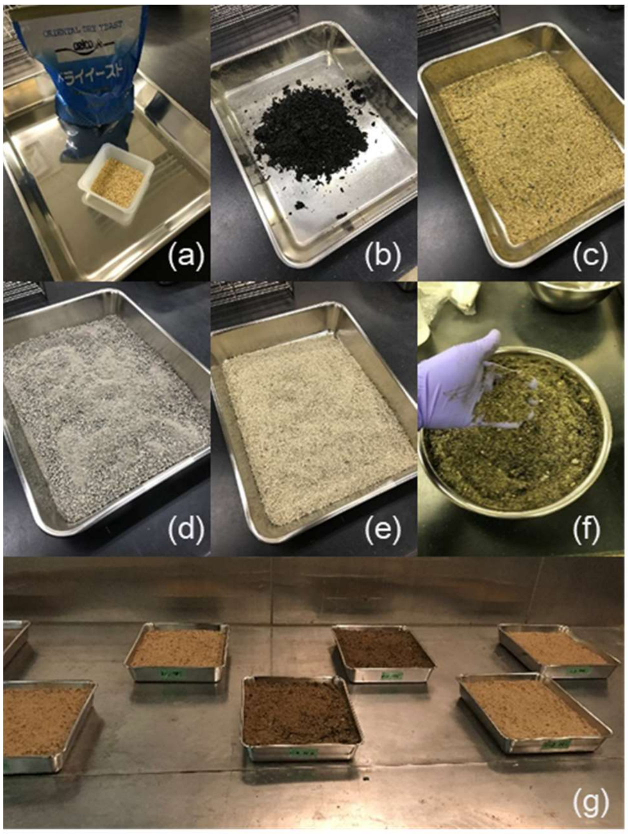


Fig. 1. Materials and solidification experimental processes.

Table 1. Composition of the materials.

| Specimen type | Dry yeast | Compost | no microbe |
|---|---|---|---|
| Mountain sand | 3,000 g | 2,700 g | 3,000 g |
| MINEKARU | 15 g | 15 g | 15 g |
| KEIKARU | 30 g | 30 g | 30 g |
| $Ca(NO_3)_2 \cdot 4H_2O$ | 24 g | 24 g | 24 g |
| glucose | 5 g | 5 g | 5 g |
| microorganism | 5 g (dry yeast) | 300 g (leaf mold) | - |

## 2.3 Measurement and analysis

The hardness was measured using a soil hardness tester (Fig. 2(a), Yamanaka flat type for soft ground, FUJIWARA SCIENTIFIC). The hardness index was measured at 3 to 5 points on each specimen, and the average value was converted to strength (MPa = N/mm$^2$) according to the conversion table.

The pH was measured using a needle-type pH meter (Fig. 2(b), pH5S, CEM Corporation). After moistening the tip of the probe with pure water, the pH was measured by piercing the inside of the specimen.

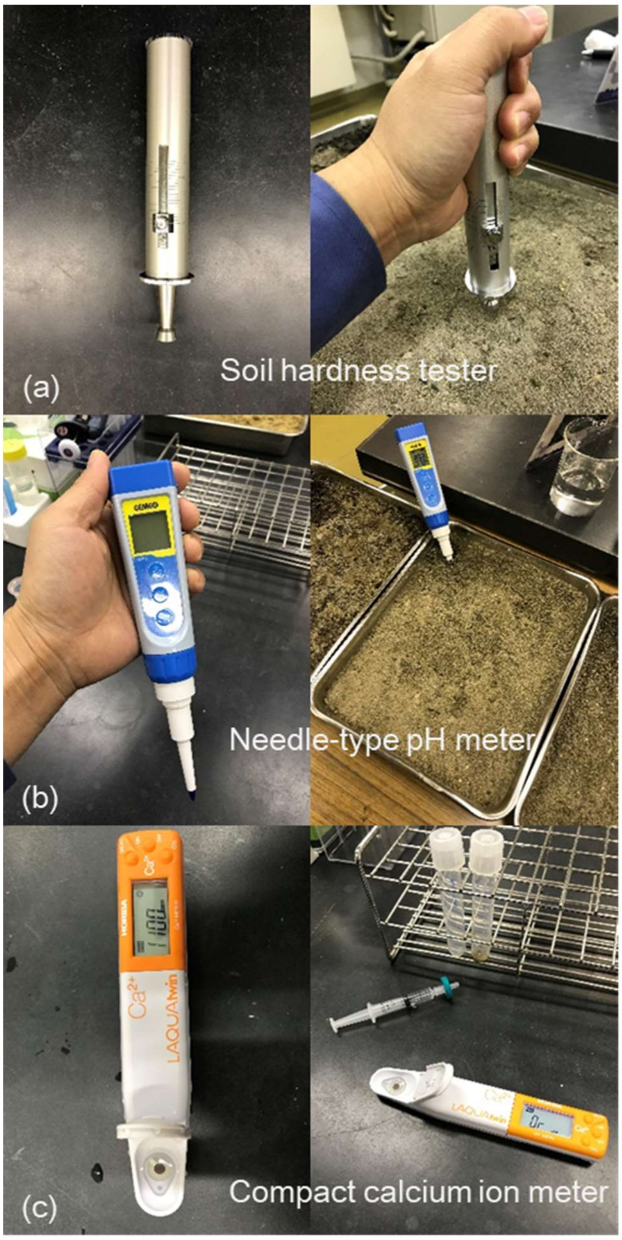


Fig. 2. Measurement and analysis of specimen.

The Calcium ion ($Ca^{2+}$) concentration was analyzed using a compact ion meter (Fig. 2(c), LAQUAtwin-Ca-11, HORIBA). Several grams of each sample were collected with a spatula and diluted 100-fold with pure water. The solution filtered through 0.45-µm filter was measured three times and the average was used as the data point. The amount of free $Ca^{2+}$ that was not carbonated in the specimen was measured.

## 3 RESULTS

Figure 3 shows a photograph of each specimen removed from the tray after curing. The specimen using dry yeast formed hard stone-like solids (Fig. 3(a)). In contrast, no solidified body was observed in the specimen using compost (Fig. 3(b)). Further, in the specimen without any microorganism addition, although solidification through drying shrinkage was observed, the formation of a firm solidified body was not observed (Fig. 3(c)).

These results strongly suggest that a reaction with dry yeast can solidify sandy soils. Figure 4 shows detailed data on the variations in hardness (Fig. 4(a)), pH (Fig. 4(b)), and $Ca^{2+}$ concentration (Fig. 4(c)) over time for each specimen, which are also described below.

### 3.1 Development of hardness

The specimen using dry yeast showed sufficient strength (1 MPa) after five days of curing that would be applicable for soft ground improvement. After twelve days of curing, the strength of the specimen reached 10 MPa, with a maximum of 14 MPa recorded.

The specimen using compost did not show sufficient strength after fourteen days of curing. The maximum strength of the specimen recorded was 0.26 MPa.

The specimen without any microorganism addition showed no strength after fourteen days of curing.

### 3.2 Stabilization of alkalescent condition

The specimen using dry yeast had a relatively low pH for the first four days of curing. After five days of curing, the pH increased, and, after six days, a pH of approximately 8.0 was maintained, which is considered favorable for mineralization.

The specimen using compost revealed the same pH trend, but did not reach a pH of 8.0. The pH of the compost (leaf mold) likely had an effect on this result.

The specimen without any microorganism addition also revealed the same pH trend, but did not reach a pH of 7.5, which meant conditions were unfavorable for mineralization. It is possible that unintentional contamination microbes reacted with glucose to generate organic acids.

### 3.3 Decrease in calcium ion concentration

The $Ca^{2+}$ concentration of the specimen using dry yeast decreased each day. On the fourth day of curing, it greatly decreased. After fourteen days of curing, it had decreased to one tenth the concentration (800 ppm) compared to the start of curing (8,700 ppm).

The $Ca^{2+}$ concentration in the specimen using compost also decreased to about half.

The $Ca^{2+}$ concentration in the specimen without any microorganism addition showed no significant decrease.

It is considered that the more the $Ca^{2+}$ decreases, the more mineralization progresses. These data reveal that the mineralization reaction was highly active in the specimens using dry yeast and, as a result, high strength was observed.

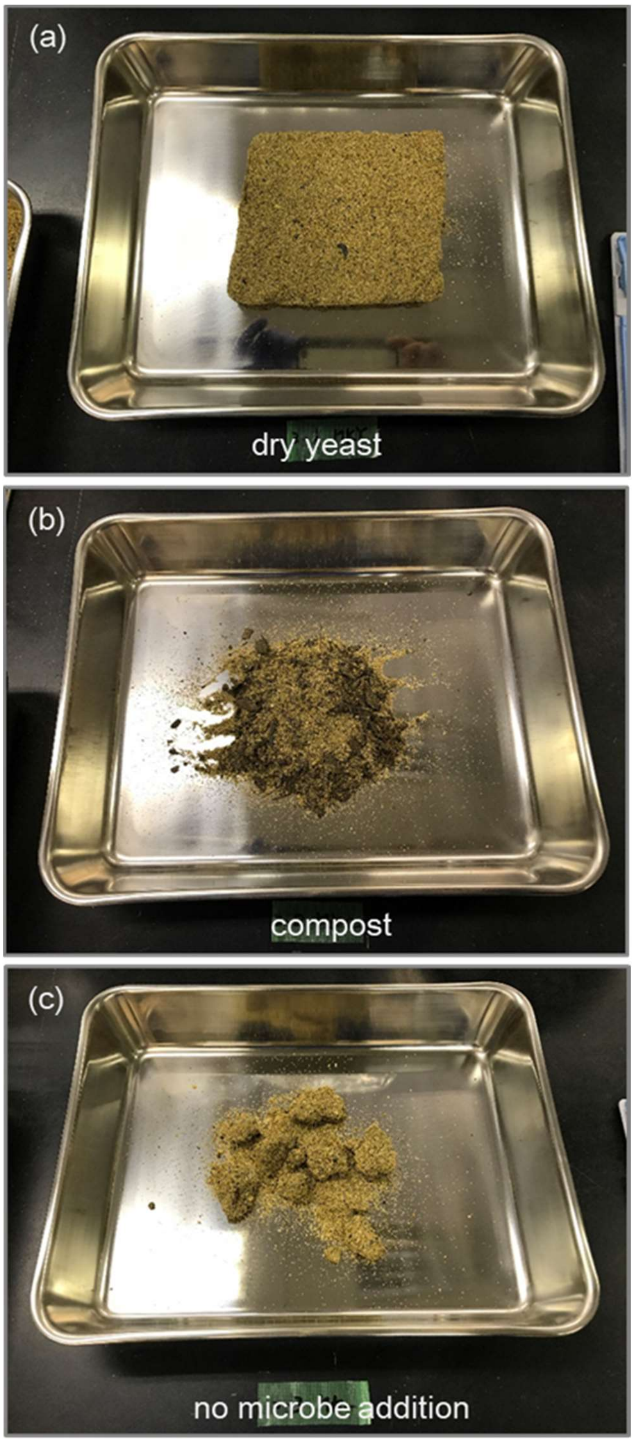


Fig. 3. Solidification status of specimen.

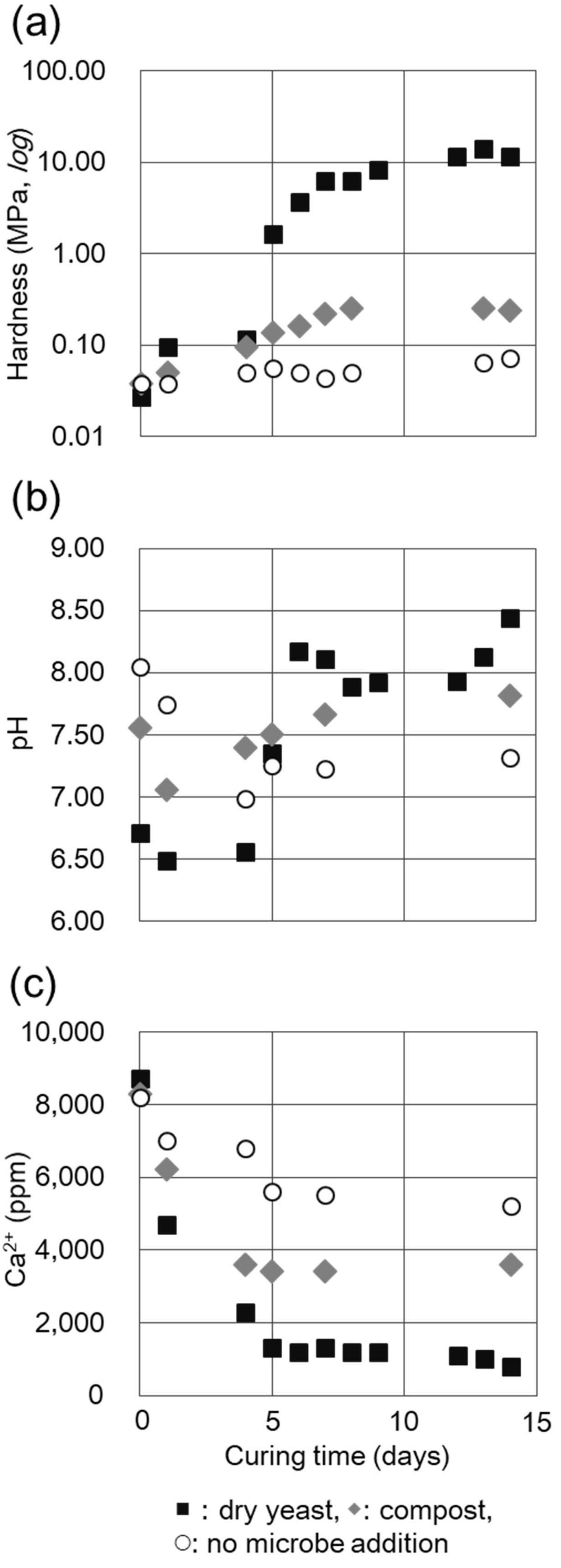


Fig. 4. Hardness, pH and $Ca^{2+}$ concentration variations in the specimens.

## 4 DISCUSSION

### 4.1 Sandy soil solidification technique

We achieved sandy soil solidification with a simple method. There are two key points of this technique.

One is the use of baker's dry yeast for the microorganism reaction. High quality dry yeast is easily available and widely used. Because the quality is consistent, it is easy to handle even if the users are not microbiologists with professional knowledge and skills. Unlike ureolytic bacteria (DeJong et al., 2006; Whiffin et al., 2007; van Paassen et al., 2010), there is no concern about problems caused by the production of ammonia, such as bad odor in the surrounding environment and nitrogen contamination of the land.

Another is the use of slag fertilizer for pH control of the sandy soil. In the past, dry yeast had been used for bio-mineralization, but expensive chemical reagents were utilized for pH control of the specimens (Kawasaki et al., 2006). In contrast, slag fertilizers are in sufficient supply and inexpensive. Furthermore, because the alkali adjusting ability of slag fertilizer is significant, a small amount is sufficient for sandy soil. It is hypothesized that soil solidification based on this technique is possible even for soils that are not sandy, if the mixing amount is examined. It is suggested that the solidification of soils with varying properties is possible.

However, there is certain limitations in the practical application on a ground improvement site. In this study, it took five days for the specimens to develop sufficient strength. The curing time is extremely long and needs to be reduced to one day or two days. In large scale field experiment using ureolytic bacteria, sandy soil hardened due to bio-cementation was observed in one day of curing (van Paassen et al., 2010). Furthermore, it has been suggested that bio-mineralization reaction even under low temperature conditions (Kawasaki et al., 2010). If the curing time could be shortened, it is expected that the field practicality would be enhanced except in the extreme cold season. In addition, the solidification experiment was conducted in a shallow stainless tray with a depth of approximately 50 mm. At this thickness, the oxygen was able to sufficiently reach the specimens, and the aerobic reaction of the microorganisms (yeast) proceeded favorably. For the application of this technique to ground improvement, it is necessary to examine this method in terms of the depth that the oxygen can be supplied.

### 4.2 Applications other than ground improvement

In our study, no environmentally harmful materials were used. Dry yeast and glucose were used as food; MINEKARU, KEIKARU, and calcium nitrate were used as agricultural fertilizer. These materials are all safe for the environment, if used properly. Moreover, it is considered that the strength of the specimen could be adjusted by examining the calcium ion supply and pH levels, and therefore it is possible to derive a soft solid from sandy soil. Therefore, this technique can be used not only for ground improvement, but also for other sandy soil applications. Agricultural land utilization is also conceivable by adding appropriately nutrient salts to fertilize and lightly solidify sandy soil.

Based on this sandy soil solidification experiment, we are developing a sandy soil improvement technique and, in the near future, would like to consider its application to agricultural land use and greening technology.

## 5 CONCLUSIONS

A simple and environmentally friendly soil solidification technique was developed. Sandy soil was solidified to 1–10 MPa of strength by simply mixing dry yeast and slag fertilizer, adding water, and letting it cure. Since no environmentally harmful materials were used, this technique is considered to be highly applicable to agricultural land use and greening technologies.


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