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# The influence of curing time on properties of the sand columns cemented by bio-barium phosphate

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## HIGHLIGHTS

- The bio-barium phosphate slurry could be applied to bind loose sandy soil grains.
- Chemical composition and shape of bio-barium phosphate slurry were analyzed.
- Dust grains could be consolidated by spraying bio-phosphate cement.

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## ABSTRACT

Loose quartz sand grains can well be cemented by microbially-induced barium phosphate precipitation into a sand column. The bio-barium phosphate slurry was composed mainly of $BaHPO_4$, and this was assessed through X-ray diffraction (XRD) analysis. The average compressive strength of sand columns increases with curing time, and increases when the content of bio-phosphate slurry is 20% and 30%wt. The results suggest the best curing time is 7 days, and the optimum content of bio-barium phosphate is 30%wt. Scanning electron microscopy (SEM) images of the sand columns showed the morphology of the cementation products is block, dumbbell-shaped, and spherical, and the products' particles can continue to grow in wet-dry circulation conditions. The sand columns ($\phi$5 cm × 5 cm) could be cemented by bio-$BaHPO_4$, and its average strength was 0.6 Mpa. The consolidation layer of dust grains was formed after spraying 1 time and 3 times of bio-$BaHPO_4$ cement, and wind erosion rate of dust was 5 $g/m^2/h$ and 0 $g/m^2/h$, respectively. The mixture of $NaBaPO_4$ and $Ba_5(PO_4)_3OH$ under different time was selected and applied to bind loose sand particles, results indicating it could not glue loose sand grains.



## 1. Introduction

The lack of infrastructure, the demand for construction land has gradually become a social issue that cannot be ignored with the rapid increase of the urban population. In China, about ten million people are transferred from rural areas to major cities each year, and the demand for infrastructure becomes more and more prominent [1]. However, the newly expanded infrastructure is largely limited by the nature of soil, therefore, needs to be improved to meet the engineering demands.

Most of the traditional foundation improvement measures are the use of mechanical vibration and synthetic grouting to achieve soil reinforcement. Common types of chemical grouting materials include water glass, acrylic amines, lignins, polyurethanes, epoxies, and methacrylates. Although the effect of foundation reinforcement is better, but chemical grouting materials are chemically toxic, posing a potential safety hazard to the human body and the environment. As the most common cementitious material, Portland cement can be used for foundation reinforcement, but it also has the disadvantages of high energy consumption and environmental pollution. Therefore, it is necessary to develop a new type of sustainable cementitious material to solve the problems of traditional grouting material in foundation treatment.

Some microorganisms widely found in nature can induce precipitation of calcium carbonate, cement the loose sandy soil particles into a whole and effectively improve the engineering properties of sandy soil [2]. This process is called microbiologically-induced calcium carbonate precipitation (MICP) and the calcium carbonate

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product as a new generation of cementitious material, ie, bio-cement. It is expected to be applied to consolidation foundation, slope stabilization, desert settlement because bio-cement has many advantages such as rapid and efficient preparation process and easy control.

The definition of bio-cement is the use of microbial-induced mineralization to form a gelation of minerals, of which calcium carbonate (bio-calcite cement) is the most widely investigated by geologists, biologists, materials scientists, etc. [3–15]. Based on the cementation characteristics of bio-calcite cement, the technique can greatly improve the mechanical properties of sandy soil [16–18]. A large quantity of ammonia gas is released during the process of microbially-induced carbonate precipitation, which can pollute the environment during the cementation process [19,20]. A new binder is taken into consideration in response to this issue. Phosphate minerals can be precipitated by microorganism mineralization due to the existence of phosphate mineralization microbes in nature.

*Bacillus-Subtilis* was chosen through experimental screening, and this microorganism can secrete a certain enzyme which can constantly hydrolyze organic phosphate monoester in bacterial solution [21,22]. Finally, phosphate ions are obtained. Different ingredients of phosphate minerals can be synthesized by phosphate ions reacting with different metal cations. Therefore, a suitable bio-phosphate mineral is applied to bind loose sandy soil grains. The micro-structure and strength of sand columns cemented by bio-phosphate cement were characterized under different curing times by scanning electron microscopy and electronic universal testing machine, respectively. The microbiological method is environmentally friendly and has potential applications in consolidation foundation, slope stabilization, desert settlement, and so on.

## 2. Experiments and methods

### 2.1. Materials

*Bacillus-Subtilis* was selected according to literature reported [23]. The microorganism was cultured through a specific nutrient solution (pH = 7, Mixture liquid of peptone and beef extract). Organic phosphate monoester was purchased from Sinopharm Chemical Reagent Co., Ltd. The 0.125 mol/L of organic phosphate monoester was produced prior to the cementation experiment. The aggregates were purchased from a quartz sand plant, and the particle size was less than 300 μm.

### 2.2. Microbially-induced precipitation of barium phosphate

80 mL of organic phosphate monoester solution was poured into 1 L of *Bacillus-Subtilis* liquid. The reaction solution was kept in a 30 ± 2 °C oven for 12 h. After 12 h, 1 mol of $BaCl_2{\cdot}2H_2O$ powers were added to above reaction solution, and kept for 12 h at ambient temperature. Finally, the bio-barium phosphate (pH = 8.2) was obtained by filtering the supernatant.

### 2.3. Specimens preparation

A certain mass of bio-barium phosphate accounted for 20–50% wt of the sand weight was dumped into a round mold (diameter 3 cm, height 6 cm), as shown in Fig. 1. The speed of the agitator was 90 rmp/min for 5 min. Each group of specimens contained 3 samples and was cured in a wet-dry circulation cure box for 1, 3 and 7 days. Finally, these specimens were kept in air for 21 days (30 ± 2 °C) after 1, 3, and 7 days.

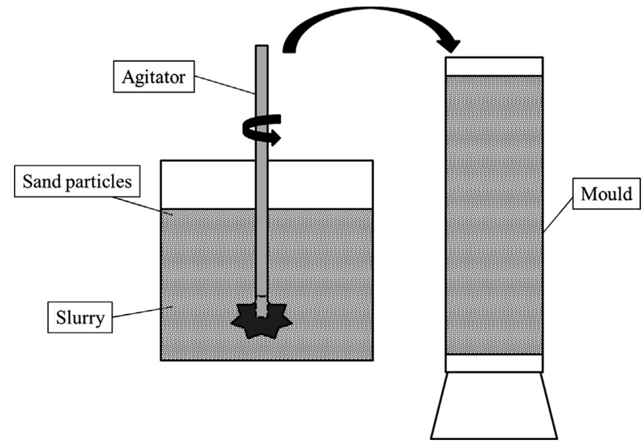


**Fig. 1.** Schematic diagram of the mixing process.

### 2.4. Sand columns cemented by other bio-barium phosphate

80 mL of organic phosphate monoester solution was poured into 1 L of *Bacillus-Subtilis* liquid. After standing 12 h, the pH of the reaction solution was adjusted to 11 with dilute sodium hydroxide solution. The same molar amount of $BaCl_2{\cdot}2H_2O$ was added to the above solution, a large number of white precipitates generated and kept 0, 6, 12, 24, 36, and 48 h at room temperature. The precipitates were obtained by filtering the supernatant. Quartz sand and 40%wt of the sediment at different setting time were completely mixed by mechanical stirring. All biological mortar were poured into a round mold (diameter 3 cm, height 6 cm), and they were dried at 30 ± 2 °C for 21 days.

### 2.5. Samples characterization

The chemical composition of samples was examined by Bruker D8-Discover X-ray diffraction (XRD, 40 kV, 40 mA, $\lambda$ = 1.5406 Å). Morphology and elements of the specimens were measured via scanning electron microscopy (SEM, operating voltage 20 kV) with genesis 60S energy dispersive X-ray spectroscopy (EDS) spectroscopy system. Compressive strength of sand columns was tested by SANS CMT 8502 electronic universal testing machine accompanied by a load rate of 1 mm/min.

## 3. Results and discussion

### 3.1. Chemical composition of bio-barium phosphate samples and the sand columns

The XRD analysis of the bio-barium phosphate hardened slurry confirms that the cementation material is the barium hydrogen phosphate ($BaHPO_4$, JCPDS Card No. 17-0929), as shown in Fig. 2a. Fig. 2b shows chemical composition of the sand column is mainly the mixture of barium hydrogen phosphate (JCPDS Card No. 17-0929) and quartz sand (JCPDS Card No. 86-1630). Therefore, the main ingredient of the cementitious product is the cementitious material of $BaHPO_4$. The formation process of the bio-$BaHPO_4$ is as follows:

### 3.2. Influence of curing time on the compressive strength of sand columns

Fig. 3 indicates that the influence of curing time on the strength of sand columns. The relationship between average strength and curing time is represented in Fig. 3. The sand columns