Construction and Building Materials 120 (2016) 623–629

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Properties of biocemented, fiber reinforced sand

Sun-Gyu Choi [a], Kejin Wang [a], Jian Chu [b,*]

[a] Civil, Construction and Environmental Engineering, Iowa State University, 813 Bissell Rd., Ames 50011, IA, USA
[b] School of Civil and Environmental Engineering, Nanyang Technological University, Blk N1, 50 Nanyang Ave, Singapore 639798, Singapore

HIGHLIGHTS

- PVA fibers can be used to improve the engineering properties of biocemented sand.
- The use of fibers enhances the MICP process by bridging the pores in sand.
- The strength of sand increases with the calcium carbonate content and fiber content.
- The use of fiber increases the failure strains and reduces the brittleness of sand.

ARTICLE INFO

Article history:
Received 7 December 2015
Received in revised form 7 May 2016
Accepted 19 May 2016
Available online 1 June 2016

Keywords:
MICP (A)
Fiber (A)
Unconfined compressive strength (C)
Tensile strength (C)
Biocement (B)
Calcium carbonate content (A)

ABSTRACT

This paper presents a study on the use of PVA fibers and biocement to improve the engineering properties of Ottawa silica sand. The fibers used were at 0.0, 0.4 and 0.8% by weight of the sand. The biocement was produced through a microbial induced calcium carbonate precipitation (MICP) process. Unconfined compressive strength, splitting tensile strength, and permeability tests were carried out to evaluate the engineering properties of the biocemented, fiber reinforced sand. The calcium carbonate content for each sample was also measured. The microstructure of the biocemented sand was observed under a scanning electron microscope. The testing results indicate that the use of fibers facilitates the MICP process in sand by bridging the pores in sand particles. As a result, the unconfined compressive strength and the splitting tensile strength of the biocemented, fiber reinforced sand have increased by 138% and 186%, respectively; the permeability has reduced by 126%, and the brittleness (expressed as the ratio between unconfined compressive strength and splitting tensile strength) is reduced by a half when compared with those of untreated sand.

1. Introduction

Portland cement, along with other cementitious materials such as lime, slag, and fly ash, has been widely used for soil modification/stabilization for many decades. It has been proven that the use of cement in soil can improve the engineering properties of soil, such as increasing the compressive strength of sand. On the other hand, the use of cement also makes the soil to become more brittle which is not desirable. To overcome this difficulty, fibers are sometimes use together with cement to improve the ductility of cement treated soil [1–3].

Recent studies have shown that some microorganisms (i. e., *Bacillus* sp. and *Sporosarcina* sp.) in the medium contained urea and calcium ions can induce precipitation of calcite in between soil particles through the MICP process and thus increase the shear strength and reduce the permeability of soil [4–13]. The effectiveness of a MICP process is mainly governed by four elements [5–13]: (1) calcium ion concentration, (2) dissolved inorganic carbon (DIC) concentration, (3) pH, and (4) availability of nucleation sites. These elements are in turn affected by the types and concentrations of bacteria, nutrients, and reagent supplied to the system. Currently, the effect of the MICP process on soil is evaluated based on mainly the unconfined compressive strength of soil. When fiber is used, the ductility of the soil will be improved and soil can even have tensile strength. Therefore, it becomes necessary to evaluate the tensile strength and the brittleness of soils improved by firer reinforced, biocement treated soil. Such studies are rare so far. The objective of this study is to investigate how the soil properties are affected by a combined use of fibers and biocement in terms of compressive and tensile strength, permeability and brittleness, as well as the change in microstructure of the soil.

In this study, PVA fibers at dosages of 0.0, 0.4 and 0.8% by weight were used together with biocement to treat Ottawa silica

* Corresponding author.
E-mail address: CJCHU@ntu.edu.sg (J. Chu).

http://dx.doi.org/10.1016/j.conbuildmat.2016.05.124
0950-0618/

sand. The compressive strength, tensile strength, permeability, and calcite content produced through the MICP process in sand were measured to assess the change in soil properties. The detailed experimental work and testing results are presented in the following.

2. Experimental work

2.1. Materials

PVA fiber, with 0.1 mm in diameter and 12 mm in length, was used. The key properties of the fiber are shown in Table 1.

Ottawa silica sand as described in ASTM C778 as a standard sand was used for this study. The has grain sizes of this sand were in between 0.6 mm (sieve #30) and 0.85 mm (sieve #20) with a mean grain size of 0.73 mm. Its specific gravity was 2.65. Other materials used included calcium chloride and urea.

2.2. Microorganism

The microorganism used was Freeze-dried *Bacillus* Sp. (American Type Culture Collection, ATCC 11859). The reason to use freeze-dried microorganisms was to facilitate the storage and transport of a large amount of microorganism for future projects.

The medium for culturing *Bacillus* Sp. was made of a yeast extract (20 g), $(NH_4)_2SO_4$ (10 g), and a 0.13 M Tris buffer (pH = 9.0) solution [13,14]. The prepared medium was then sterilized in an autoclave at 121 °C for 15 min. The sterilized microorganism was injected into the medium and cultured at a 30 °C incubator for 3–4 days. The microorganism was subsequently freeze-dried using lyophilizer (or Freeze Dryer). The freeze-dried *Bacillus* Sp. was then placed into sterilized vial and stored in a refrigerator with a temperature of −10 °C. When using the freeze-dried microorganism, it was mixed with distilled water in a sterilized glass bottle and stirred gently in an incubator for several hours. Two sets of urease activity tests were conducted to identify the urease activity of lyophilized *Bacillus* Sp. The first set of the tests was to investigate the effect of reaction time on urease activity of the mixture, and the second set of the test to examine the effect of lyophilized *Bacillus* Sp. concentration on urease activity of the mixture. These tests confirmed that the lyophilized *Bacillus* Sp. was suitable to be used for MICP purpose.

In the first series of the tests, 0.5 g freeze-dried *Bacillus* Sp. was mixed with 1 L distilled water. The mixture was then incubated in a glass bottle at a temperature of 30 °C while stirring at a rate of 150 rpm. After incubation, 5 ml of the prepared bacterial suspension was added to 50 ml of 1 M urea solution. The ammonium ion (NH_4^+) concentrations in the mixtures were measured with time using an electric conductometer [15]. Urease activity was defined as the amount of ammonium produced per minute from 1 M urea solution. A high NH_4^+ ion concentration (mM/L) indicates a high urease activity in the mixture. To determine the optimized duration of stirring, 4 different incubation periods of 1, 2, 4, and 8 h were experimented. The results of the 4 tests are shown in Fig. 1a in which urease activity is plotted versus time. As seen from Figs. 1a and 2 hours of incubation provided the highest urea reaction, and therefore was used in this study.

The effect of the amount of biomass used on the urease activity was also studied. Tests with 4 different amounts of freeze-dried *Bacillus* Sp., 0.5, 1.0, 1.5, and 2.0 g, were mixed with 1 L distilled water. An incubation time of 2 h were used. After incubation, 5 ml of the bacterial suspension was mixed with 50 ml of 1 M urea solution. The ammonium ion (NH_4^+) concentrations in the mixture were measured with time. The results of the 4 tests are shown in Fig. 1b. It can be seen that the higher the amount of biomass, the higher the urease activity. Using Fig. 1b, the amount of freeze-dried *Bacillus* Sp. required can be selected depending on the urease activity required. A biomass of 1.5 g per litter of water was used in this study. The corresponding urease activity was 3.7 mM/min, which is smaller than that used in other studies [15,16] but still adequate. Previous studies have shown that excessively high urease activity may result in a rapid precipitation of calcite onto the top surface of a soil sample and thus blocking the delivery of biomass and regents to deeper depths of the sample.

2.3. Sample preparation

A total of 18 tests are reported in this paper as listed in Table 2. To prepare for the fiber reinforced, biocemented sand samples, Ottawa sand was firstly placed into a Hobart mixer. Dry PVA fiber (at a ratio of either 0.4 or 0.8% by weight) was added into dry sand and mixed by hand until the fiber was uniformly distributed. Distilled water was added the fiber and sand mixture to achieve a 7% water content. After mixing, 324 g of the mixture was placed into a 5 cm in diameter by 10 cm height plastic cylinder in 10 layers with each layer compacted to be 1 cm height. After formation of a sample, its unit weight was about 1.65 Mg/m^3. The reason for using 10 layers was to ensure a uniform fiber distribution in the sample [2]. Six samples were prepared for each of the 3 fiber contents of 0.0, 0.4, and 0.8% by weight as shown in Table 2.

To facilitate drainage and avoid calcite precipitation on the top surface of the sample, a piece of 3 M scotch Brite scouring pad was placed at each end of the sample as a filter as shown in Fig. 2.

100 ml microorganism solution was pumped into the sample from the top and drained out from the bottom as shown in Fig. 2. As mentioned earlier, the biomass solution was made of freeze-dried *Bacillus* Sp. at a concentration of 1.5 g/L and incubated for 2 h. For the first treatment, the microorganism solution was circulated for 3 h using a pump. Then 500 ml of urea and calcium chloride solution (0.3 M by 1:1 ratio) was used and circulated for 9 h. After one cycle (Microorganism and urea/calcium chloride solution), fresh microorganism solution and urea and calcium chloride solution were used to circulate in sand. Such a microorganism solution and urea/calcium chloride solution was repeated two cycles a day for 7 days. The production of calcium carbonate in the samples was observed.

2.4. Tests and methods

After the samples were treated, water permeability tests were carried out for each sample. Out of the 6 samples at each fiber content, 3 samples were used for unconfined compression tests and another 3 for splitting tensile strength tests. After the tests, 5 g of materials were collected from each sample and used for the measurement of calcium carbonate. The method adopted for the measurement of calcium carbonate was ASTM D4373 [17]. The permeability test was determined using a falling head method. The unconfined compressive strength test was determined according to ASTM D4219 [18]. The splitting tensile strength test (Brazilian test) was conducted according to ASTM C496 [19].

Table 1
Properties of PVA fiber.

PVA fiber	Specific gravity	Length (mm)	Diameter (mm)	Tensile strength (MPa)	Young's modulus (MPa)
RECS 100L	1.3	12	0.1	1078	25,000