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Microscopic investigation of interparticle-interaction between sand particles and biopolymer

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ABSTRACT: Due to the promising potential of biopolymer as an environmentally friendly soil binder, biopolymers are actively attempted for soil strengthening through various research, nowadays. However, most previous studies have focused on the mechanical behavior of biopolymer-treated soils with the lack of detail microscopic investigation. Thus, this study aims to investigate the inter-particle bonding characteristics of biopolymer-treated coarse grain soils with microscopic observation using microfluidic chip apparatus. As a result, inter-particle bonding behavior between coarse soil particles is visualized with microscopic observation. The number of inter-particle bonds (bridges) shows dependency on soil porosity and biopolymer to soil ratio in mass. The trend of biopolymer film matrix formation is analyzed in terms of number of connections and the direction of connections, under various porosity and biopolymer solution concentration ($m_{biopolymer}/m_{water}$) conditions.

1 INTRODUCTION

For sustainable geotechnical engineering, biopolymer has been recently suggested due to its promising potential of high strengthening effect with its environmentally friendly feature. Many researches have been conducted to verify effectiveness of biopolymer, as a result, its comparable strengthening effect compared to cement has been evaluated (Ayeldeen et al. 2017; Cabalar et al. 2017; Latifi et al. 2016). Biopolymers have shown significant improvement on geotechnical engineering parameters including unconfined compressive strength, inter-particle cohesion and friction angle.

However, most previous studies have focused on the mechanical behavior of biopolymer-treated soils with the lack of detailed microscopic investigation. Thus, this study aims to investigate the inter-particle bonding characteristics of biopolymer-treated coarse grain soils with microscopic observation using microfluidic chip (MFC) apparatus.

Under the assumption that inter-particle bonding between biopolymer and coarse particles are governed by the soil density (porosity) and biopolymer hydrogel rheology, the inter-particle bonds (biopolymer film bridges) is monitored under the different conditions of soil density and biopolymer solution concentration. The trend of inter-particle bonds formation is analyzed in terms of biopolymer bridge direction with length variation, in this study.

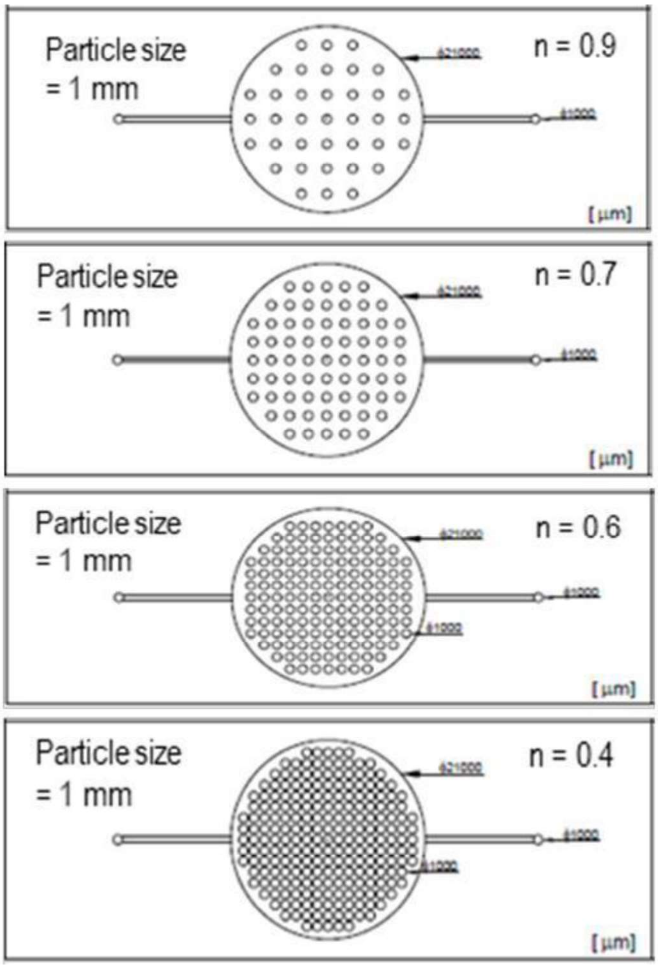

Figure 1 Example of microfluidic chips (MFCs).

2 TEST MATERIALS AND METHOD

2.1 *Test materials*

The customized MFCs are manufactured using Polydimethylsiloxane as shown in Figure 1. In detail, the diameter of representative sand particle is decided as 1 mm, and the porosity condition is controlled as 0.4, 0.6, 0.7, and 0.9 to investigate theoretical trend including representative practical condition (n = 0.3 – 0.4). The porosity is calculated using void volume according to distance between sand particles under homogeneous orthogonal alignment. The calculation is performed under the assumption of 2-dimensional diagram since the height of MFCs is negligible.

Xanthan gum biopolymer is used in this study. The xanthan gum is byproduct by the Xanthomonas campestris bacteria, and it is composed two glucoses, two mannoses, and one glucuronic acid. It forms hydrogel when it absorbs water due to the hydrophilic characteristic of biopolymer.

The biopolymer solution is prepared by mixing biopolymer powder and water using pneumatic mixer. The biopolymer solution concentration ($m_{biopolymer}/m_{water}$) is 4.74%, which means 10% of ratio of biopolymer content to sand ($m_{biopolymer}/m_{soil}$) at the porosity of 0.6.

2.2 *Test methods*

The biopolymer solution is precisely injected into MFCs using a syringe pump (New Era Pump System NE300) with an injection ratio of 50 uL/min. The biopolymer solution injected into MFCs are dried at the room temperature for 10 days until the biopolymer matrix is sufficiently dehydrated. The microscopic images are taken using the microscope (Zeiss Axio Imager 2) (Figure 2).

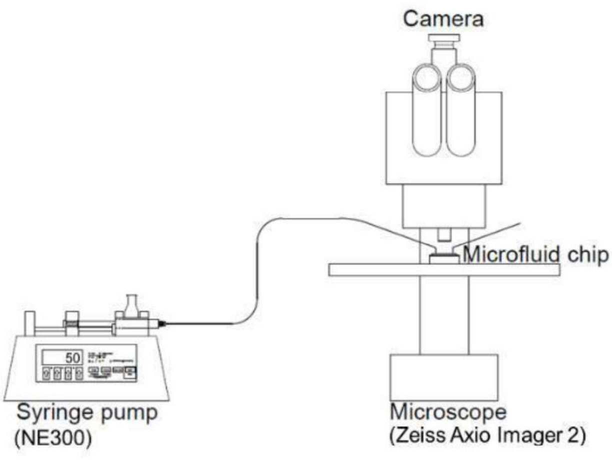

Figure 2 Experimental set-up.

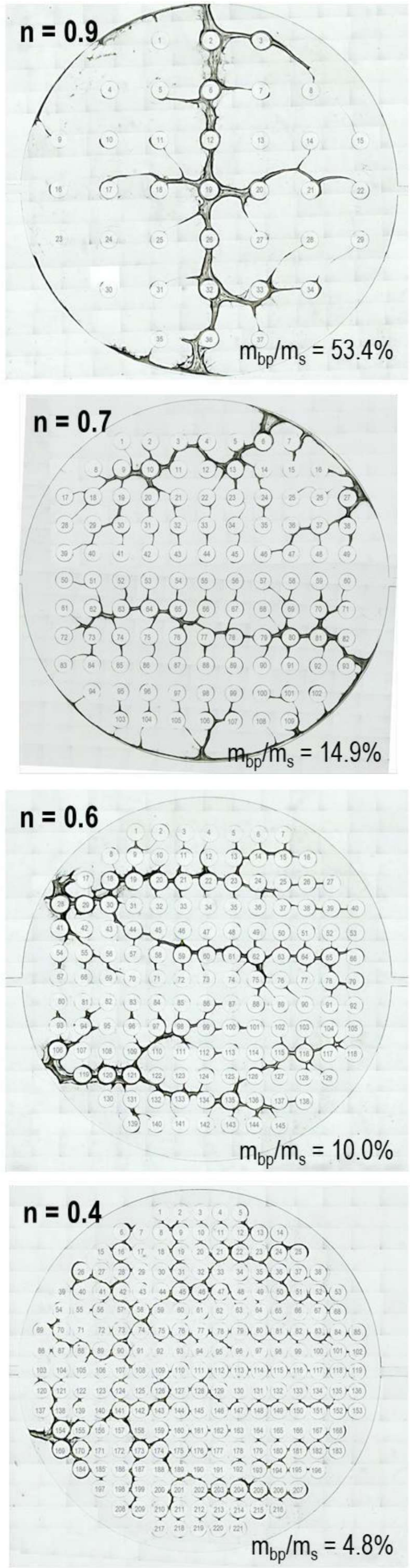

Figure 3 Biopolymer film matrix formation within microfluidic chips.

3 TEST RESULTS

3.1 *Effect of porosity – continuity of inter-particle bonds*

As shown in Figure 3, the biopolymer has a characteristic that makes continuous biopolymer film matrix between sand particles regardless of porosity. However, it seems that there is a limitation of making continuous biopolymer matrix under higher porosity condition.

In detail, the biopolymer content ($m_{biopolymer}/m_{soil}$) is differed as 53.4%, 14.9%, 10.0%, and 4.8% due to the difference of void volume with a same injection fluid concentration. Despite of higher amount of the biopolymer content ($m_{biopolymer}/m_{soil}$) than common recommended dosage (i.e. 0.5% to 2.0%) (Chang et al. 2015; Chen et al. 2013; Kavazanjian et al. 2009; Wiszniewski et al. 2017), the degree of connectivity which means how continuous a matrix is created is decreased as the porosity is decreased (Figure 6). It can be deduced that the porosity is more affected to continuous inter-particle bonds than biopolymer content ($m_{biopolymer}/m_{soil}$).

Meantime, the biopolymer film matrix is not well established in case of high porosity (n = 0.9) because the biopolymer remains as partial hydrogel status and higher porosity causes lower surface area and longer distance between sand particles.

3.2 *Effect of porosity – number of connection*

Regardless of porosity, there is a tendency to make inter-particle bonds (biopolymer film bridges) with adjacent particles in orthogonal or diagonal or both ways. Figure 4 describes the developed biopolymer film bridge formation as an example. Each sand particles are given an index number as shown in Figure 3, and the connections between each sand particle are counted using these index numbers as a colored mark as shown in Figure 4. The both of firstly and secondly-ordered diagonal trendline means that the

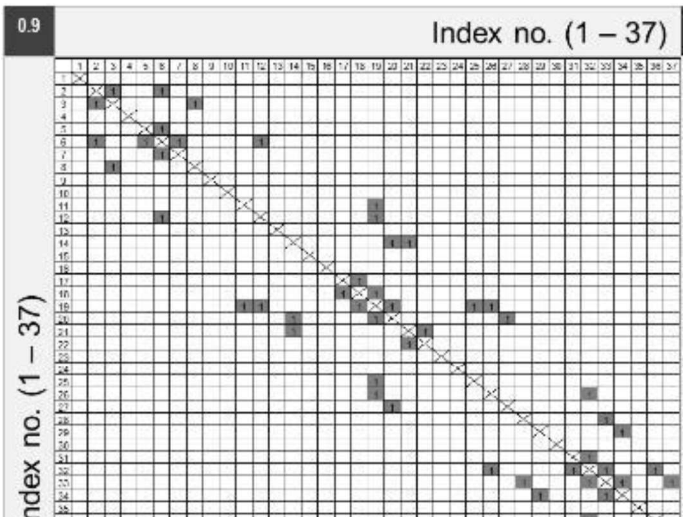

Figure 4 Trend of biopolymer film matrix formation (example of n=0.9).

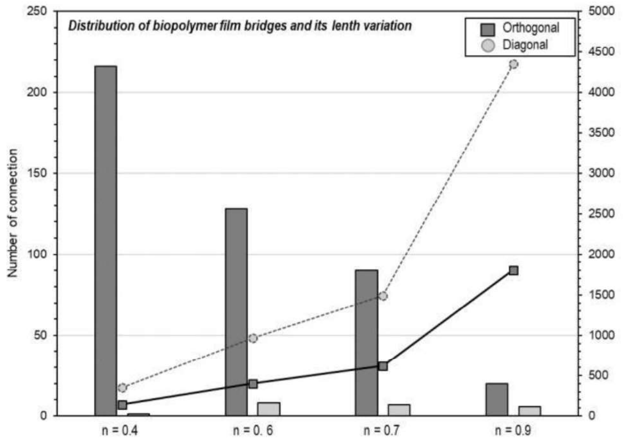

Figure 5 Distribution of biopolymer film bridges and its length variation.

biopolymer has a tendency to make a biopolymer film bridges with adjacent particles.

Contrary to direction of biopolymer film bridges formation, the porosity affects to bridge length and number of inter-particle bonds. As the porosity is risen, the bridge length becomes longer and the number of connection is decreased as shown in Figure 5.

Figure 6 describes the number of connectivity which indicates how many sand particles are connected among total sand particles. When the porosity is 0.4, there is no unconnected particles. Therefore, the connectivity refers 1 in that lower porosity condition. On the other hand, the connectivity shows decrease tendency as the porosity is enhanced. Eventually, the connectivity approximately reaches to 0.73 when the porosity is 0.9.

4 DISCUSSION

Previous studies revealed that the significant strengthening effect of biopolymer is rendered by inter-particle bonding characteristic caused by cohesion of biopolymer film matrix (Cabalar et al. 2017; Lee et al. 2017). (Chang and Cho 2018) presented the effect of cohesion enhancement as well as the effect of porosity by applying overburden stress at la-

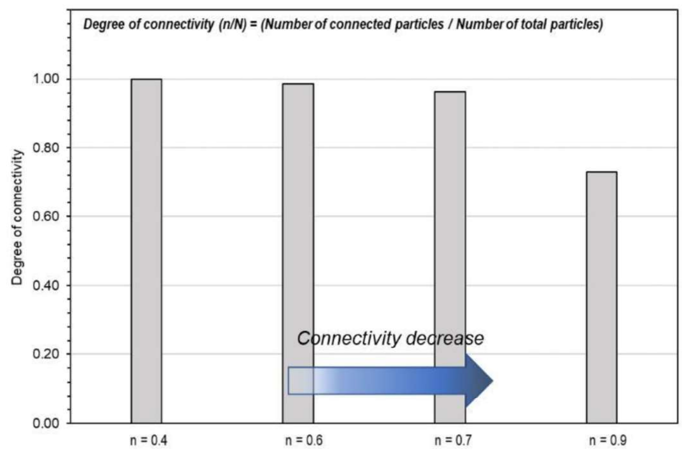

Figure 6 Degree of connectivity (bridging) with various porosi-ty conditions.

boratory direct shear experiment. In detail, the direct shear strength is enhanced as the porosity is decreased.

Though it is believed that lower porosity is effective in perspective of the strengthening effect, it should be verified under extreme porosity condition with accurate measurement. Therefore, the microscopic study is performed using MFCs, and the experimental results from this study can be explained using strengthening effect, biopolymer film bridge formation, and affecting factors including porosity and biopolymer concentration. In detail, it can be assumed that the inter-particle bonding (bridge formation) contributes to strengthening effect of soils and it is highly effective when the porosity is lower. In other words, continuous biopolymer film bridges formation is mostly affective to strengthening effect rather than bridge length, bonding direction and biopolymer concentration. The increased cohesion by biopolymer treatment can be explicated as enhanced connectivity between sand particles in terms of both connectivity and continuity.

This study tries to investigate quantitative inter-particle bonding behavior and identify affecting factors to biopolymer film bridges formation. As a result, most affecting factor to continuity and connectivity of biopolymer film bridges is presented as porosity. However, there are still several limitations: 1) not consider extremely lower porosity conditions, 2) not investigate many porosity conditions related to realistic practical conditions, and 3) not regard various particle alignment.

5 CONCLUSION

In this study, the biopolymer film bridges formation is microscopically monitored using two-dimensional MFCs. Continuity and connectivity of inter-particle bonding (biopolymer film matrix) are analyzed under various porosity condition. The findings from experimental study are following as:

- Previous studies present that the cohesion mainly enhances the strengthening effect of soils when the biopolymer treatment is conducted. This can be explained by inter-particle bonding characteristics between sand. This study reveals that the inter-particle bonding has a tendency to be occurred with adjacent particles, and the continuity and connectivity has affected by porosity condition.
- In detail, the continuity and connectivity of biopolymer film bridges are enhanced when the porosity becomes lower because of higher surface area and shorter distance between sand particles. As how many long-connected bridges are formed is affecting to inter-bonding characteristic, it can be deduced that both of continuity and connectivity are important for significant strengthening effect.
- Though microscopic quantitative analysis is performed to investigate inter-particle bonding behavior as a first attempt, there are still several limitations of considering various realistic practical porosity conditions, particle alignment, and biopolymer solution concentration.

6 ACKNOWLEDGEMENT

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