The drying effect on xanthan gum biopolymer treated sandy soil shear strength

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highlights

Xanthan gum has limited effect on the soil strength at initial stage.
Drying leads to xanthan gum bonding strength and soil cohesion increase.
Shrank brittle dry xanthan gum generates strengthening effect variability in soil.

article info

Keywords:
Biopolymer
Soil strength
Drying
Bonding property

abstract

Biopolymers are environmentally friendly materials which have shown their competitiveness in civil engineering. Researchers mentioned that drying is the crucial factor in the behaviour of biopolymer trea-ted soil, but how it influences soil strength is still unclear. This study explains how drying influences biopolymer treated soil strength, especially for the behaviour of xanthan gum biopolymer and sand inter-action during the drying. The xanthan gum biopolymer presented limited effect in the sand when water content was in a high level. With the continuous evaporation of water, bonding property from the biopolymer gradually showed up which lead to the increase of the soil shear strength (40 LC oven). However, when sample dried at the 20 LC room temperature condition, the outer surface of the sample was cemented and crystallised by the xanthan gum biopolymer while the inner part was still moist and weak cross-linked, which lead to the weak shear strength. When the water became completely evap-orated, samples under those two different drying conditions presented a significant increase in shear strength. But these results were inconsistent as the biopolymers shrank and became brittle which lead to a variability of cohesion of soil strength. The measured biopolymer bonding property presented con-sistent results to the findings in the direct shear tests. The schematic diagram of sand motion was pro-posed to illustrate the biopolymer treated sand shear performance and gave the further explanation of variability of biopolymer treated sand strength.

1. Introduction

In the natural system, the mixture of mineral, organism, gases and liquid form the soil [1]. The soil chemical and biological prop-erties play important roles in the ecological cycle. In civil engineer-ing, soil acts as a geological body which has a close relationship with engineering construction. Thus, it is important to choose proper soil and improve its physical and mechanical properties to meet the engineering standard. Grouting is a traditional soil sta-bilisation method which adds cement, lime or other chemical material into the soil to strengthen soil stability [2]. However, these traditional cementing materials will not only affect the soil pH to damage the natural environment, by the production of cement intensify the greenhouse gas emissions [3,4]. With the pro-motion of environmental awareness, it is crucial to choose eco-friendly materials for the civil engineering purpose.

In soil, plant roots secrete mucilage and bacterial or other microorganism induced EPS impact soil aggregation and tangle with roots and nearby soil to form rhizosphere to increase soil sta-bility [5,6]. Even though their content is relatively low in the soil, they still play an important role in influencing hydro conductivity, aggregation, durability and strength [7,8]. The main composition of these materials is biopolymer. Biopolymers are natural existing

polymers which often have polymeric carbohydrate structures [9]. Unlike low content natural existing biopolymers in the soil, the bio-manufacturing biopolymer induced by organisms in a factory provides in large quantity for civil engineering purposes [10]. In addition, biopolymers present high stability under different condi-tion [11,12].

Thus, some researchers are using biopolymers in civil engineer-ing projects to improve engineering material properties [13,14]. The biopolymer b-1,3/1,6-glucan has been shown to aggregate soil particles and subsequently enhance the overall soil compressive strength, whilst the same biopolymer was responsible for a posi-tive effect on the compactability, atterberg limits and swelling index of treated soil and a negative effect on the consolidation coefficient [15]. By carrying the direct shear test, unconfined com-pression test and hydraulic conductivity test, for the biopolymer treated sand, it can be found both compression and shear strength increased while the permeability decreased. [16]. It can be found that the small amount of biopolymer still had a significant effect in reducing soil erosion by enhancing soil inter-particle cohesion [17]. Researches have revealed that the soil type, biopolymer type and content are closely related to the strengthening properties [18,19]. In addition, drying is an important factor which greatly influences biopolymer treated soil property. It can be found that under different treating and curing condition (initial, drying, dry-ing and rewetting), the strengthening effects of gellan gum treated soil were quite different. The biopolymer treated soil shear strength increased regardless of the curing conditions, while its compressive strength only performed good strengthening effect in the drying condition [20]. For curing in the constant tempera-ture, with the increase of curing time from 1 to 10 weeks, the soil cohesion stress increased about 1.6 times [21]. However, how dry-ing affected soil strength is still unclear. For example, after drying for 7 days and 28 days, there were not many variations for the peak strength of the guar gum treated soil unconfined compressive test results [13].

The purpose of this research aims to investigate how drying influences biopolymer treated soil strength, especially on the beha-viour of xanthan gum biopolymer and sand interaction during the drying. By drying biopolymer treated soil to different water con-tents under different drying conditions, the direct shear tests were carried out in measuring biopolymers treated soil strength. Scan electron microscopy (SEM) analysis presented the inter-particle behaviour of the biopolymer treated soil mixture. Finally, the bonding property of biopolymers after drying was discussed to give a further explanation of how biopolymer performed under dif-ferent drying conditions.

2. Materials

2.1. Sand

Clean and uniform sand is selected as the basic material in the tests. The coefficient of uniformity (C_u) and the coefficient of gra-dation (C_c) are 2.41 and 1.28, respectively. The specific gravity of sand is 2.65. The gradation curve is presented in Fig. 1.

2.2. Biopolymer

Biopolymers are the polymeric of biomolecules which means they are environmental renewable materials. The main component of biopolymer is the polysaccharides. Xanthomonas campestris bacterium induced xanthan gum is used in the test. Xanthan is non-toxic thickening agent to prevent ingredients from separating which is normally used in the food industry [12]. The solid form of xanthan gum is a white powder which has a high hydrophilic prop-
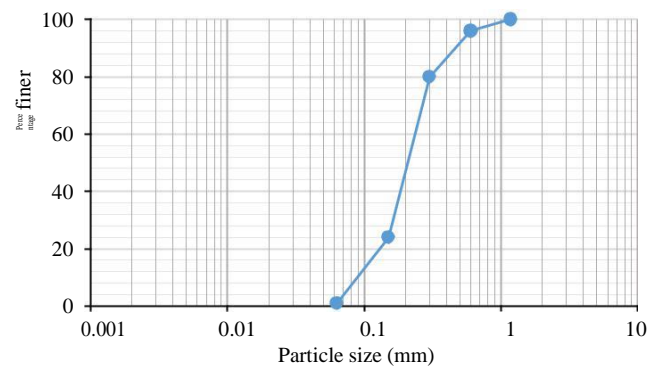

Fig. 1. Gradation curve.

erty when dissolved in water. When mixed with water properly, it forms a stable viscous gel even at low concentration. For the xan-than gum gel, it shows viscoelasticity, with an initially elastic response to shear force developing into viscous flow as the force increases [22]. In addition, xanthan gum presents high thermal and pH stability under different condition. Its rheological property remain stable under a wide range of temperature [23]. Due to environmental- friendly and the mentioned property of xanthan gum, it is expected to use xanthan gum as an organic additive in the bio-geotechnical engineering. A previous study has revealed its capability to be an engineering binder [16].

3. Test procedure

3.1. Direct shear test

In order to evaluate the performance of different concentration of biopolymer treated soil over the time, more than one hundred samples were prepared in the following method. Firstly, purified sand was mixed with a certain amount (0%, 0.25% and 0.5% of soil mass weight ratio respectively) of xanthan gum powder using an automatic rotator. Secondly, mixtures were put into the shear box and vibrated automatically to distribute the biopolymer homogeneously. Then, samples were immersed in distilled water to fully saturate, a cap was used to cover the top of the sample sur-face to avoid the expansion of mixture. The initial density of sam-ples ranged from 1.81–1.85 g/cm^3. For the next stage, all the samples were preserved in a sealed chamber for 24 h for full stabil-isation to represent the initial state (100% water content). Finally, for the properly drying, samples were treated at the room temper-ature (20 LC) or in the oven under 40 LC to reach the target water content (66%, 33% and 0%) to discuss the biopolymer effect under different drying condition. Direct shear tests were carried out under the vertical stresses of 50, 100, 200 and 300 kPa following the British Standard (BS 1377-7: 1990). The loading rate of the test was performed at 0.8 mm/min. All the samples were made and car-ried out in triplicated to minimise experimental error.

3.2. Bonding property of biopolymer

As xanthan gum is a hydrophilic material, the outer sphere of powder will hydrate while inner gum thus does not have access to water and forms clumps. Therefore xanthan gum powders should be poured carefully into the water and mixed by using mag-netic stirring. The design concentration was the same as that used in the direct shear test samples. After xanthan gum powder was dispersed in the water homogeneously, the gel solution was then cast on the substrate of the 2 cm 2 cm mould surface in Fig. 2 by using a spatula. The amount of xanthan gum gel attached to

Fig. 2. Bonding property tests machine.
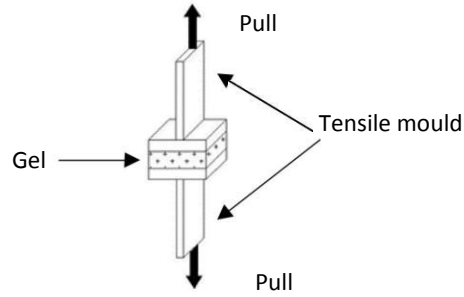
the mould was measured and kept constant each time to keep the film thickness uniform and consistency. Finally, the mould was put into 40 LC oven or at the 20 LC room temperature for drying to the design water content (66%, 33%, 0%). After the sample cooled to room temperature, the mould was put into the following Fig. 2 machine to do the bonding test. The two edges of tensile mould are both grasped by the machine which can provide mechanical stability for subsequent test. During the test, the pull out angle was set at a constant angle of 180L, while the operating velocity of the machine was set at a constant rate at 0.5 mm/min. The pull out strength against time curve is recorded and transferred to a computer by a data logger. Then the adhesive stress to peel biopolymer gel from mould can be calculated by dividing the max-imum pull out strength by mould substrate area.

3.3. Microscopic behaviour

The scanning electron microscope was applied to observe the microscopic behaviour of biopolymer treated soil. The SEM images present clear and objective observation about the interaction between the xanthan gum and sand particle.

4. Results and discussion

4.1. Strength of biopolymer treated soil in the initial state

The shear stress-strain behaviour of 0.25% and 0.5% xanthan gum treated soil and non-biopolymer treated soil is presented in Fig. 3. For the non-biopolymer treated soil, it presented the typical dense sand shear stress and strain curve. The shear strength

quickly increased to the peak, then gradually decreased, and kept constant finally. The maximum direct shear strength values were 43, 80 155 and 205 kPa for the vertical stresses of 50, 100, 200 and 300 kPa. However, the adding of xanthan gum (both 0.25% and 0.5% biopolymer treated sand) did not show any significant effect on the soil strength under every vertical stress. The xanthan gum treated soil showed a similar trend and even reduced the shear strength at some point. For the non-cohesive sand, the shear strength is mainly caused by the frictional strength between the sand particles. For the xanthan gum treated soil, due to its strong hydrophilic property, the xanthan gum absorbed water to form the uniformly dispersed hydrogel. The biopolymer solution con-nected or covered particles by its viscosity property. However, as xanthan gum biopolymer dissolved in the redundant water, it is the cross-link xanthan gum biopolymer playing the dominated role to exhibit its relatively high viscosity, adhesive and cohesion prop-erty. The water just acts as the sol in this system. Here, the content of xanthan biopolymer particles is so low in the water that most water exhibit its fluid property rather than the gel property. So there were not many differences between the clean sand and biopolymer treated sample at the initial state.

4.2. Variation of biopolymer treated soil strength with different water content after drying

4.2.1. Drying effect under different drying conditions

Some researches have revealed that adding biopolymers indeed changed the soil property, while biopolymer content and drying time are the important influence factors. It can be regarded as a biopolymeric cementation process during the drying [24]. To have
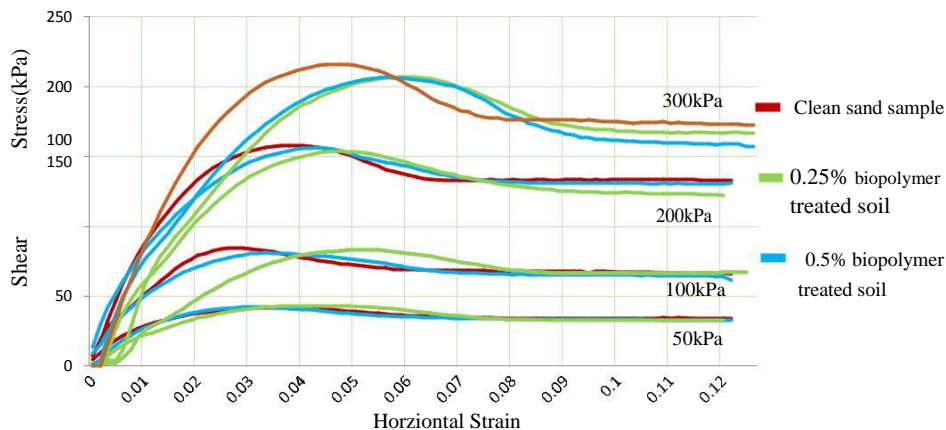
Fig. 3. Strength of biopolymers treated soil in the initial state.

a comprehensive understanding of this biopolymeric cementation process, Fig. 4 plots the biopolymers treated soil behaviour under different water content after drying under different condition (20 LC room temperature and 40 LC oven).

Like the initial stage (100% water content), the biopolymer trea-ted soil remained similar trends after drying to some extent (66% water content) in the two different drying conditions. Even though water content decreased from 100% to 66%, the fluid property still played the prominent role compared to its adhesive bonding prop-erty which means xanthan gum biopolymer gel-like property still cannot be recognized. While in the liquid state, the biopolymer solution is weak gel. The cross-link biopolymer was so weak to be broken. Thus there were not many differences between weak gel with water.

With continuous water evaporation, the dehydration of con-densed biopolymers solution gradually lead to the precipitation of biopolymer [12]. At the same time, polymeric matrix created cross-link between the sand particles. It can be seen when the water content reached 33% after drying in the 40 LC oven, there was a significant increase in shear stress for both 0.25% and 0.5% concentration biopolymer treated sand. For 0.25% biopolymer trea-ted sand, the peak shear stress increased about 1.2–1.4 times com-pared to the clean sand sample. For the 0.5% biopolymer treated sand, apparently, by adding more xanthan gum to the sand, more biopolymers can surround and connect with soil particles which lead to the high shear strength (about 1.4–1.8 times increase). It can be regarded that biopolymer solution transforms into gel state

from liquid state. Compare to the liquid, the gel has high viscous and elastic property. This viscoelastic property has a close relation-ship to the gel-adhesive strength. These polymeric adhesive com-bined sand particles to influence both cohesion and friction. The following cohesion and friction angle of the samples were calcu-lated in the Table 1. After drying to 33% water content, both 0.25% and 0.5% biopolymers treated soil cohesion increased almost three times and higher biopolymers concentration treated soil had higher cohesion (39.01 kPa to 49.86 kPa).

For the clean sand sample, there is little cohesion between the particles. Most of the strengths are provided by the friction between the particles. For the xanthan gum biopolymer treated sand, as sample cohesion was related to the gel viscosity and adhe-sive. When sample water content ranged from 100% to 66%, the xanthan gum biopolymer solution is still a weak gel which pre-sented limited effect to the viscosity and adhesive. With continu-ously drying, it can be speculated that when water content reaching some certain level after 66%, the gel-adhesive property was recognised. During desiccation, the volume of xanthan gum gel shrank accompany with the increasing of concentration of biopolymer in the solvent [25]. Besides, concentration increase can accelerate the formation of the cross-link. The more water evaporated, the high viscosity and adhesive strength of the xan-than gum biopolymer solution would have. The weak cross-link of biopolymer become stronger. These links were condensate and polymerized. This lead the gel structure to fibrils. Biopolymer fib-rils were anchored on the sand particles to connect and entangle
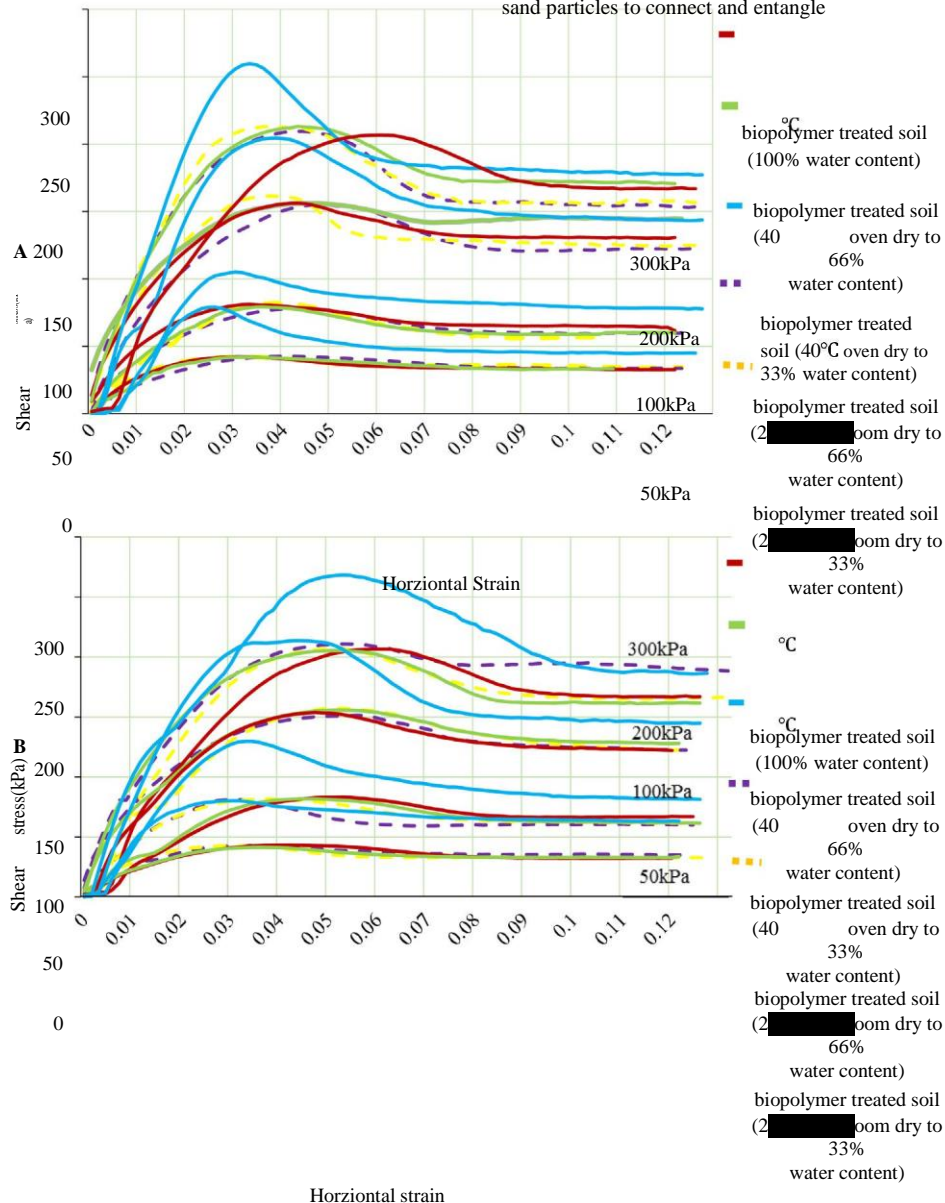

Fig. 4. Biopolymer treated soil strength variation with different water content after drying (A: 0.25% biopolymer treated soil, B: 0. 5% biopolymer treated soil).

Table 1
Shear strength parameters of biopolymer treated soil.

Xanthan Gum content	Drying condition									
	20 LC room	40 LC oven	20 LC room	40 LC oven	20 LC room	40 LC oven	20 LC room	40 LC oven	20 LC room	40 LC oven
	100% water content		66% water content after drying				33% water content after drying			
	Cohesion, c peak, [kPa]	Friction angle, / peak	Cohesion, c peak [kPa]		Friction angle, / peak		Cohesion, c peak [kPa]		Friction angle, / peak	
0.25%	11.29	34.02L	12.5	11.59	33.79L	34.18L	10.38	39.01	34.4L	37.03L
0.5%	13.69	33.46L	12.2	14.81	34L	33.27L	11.3	49.86	34.15L	37.17L

with others [26]. Thus, biopolymers had great influences on the soil cohesion which finally resulted in the strengthening of the biopolymer-soil matrix.

However, for the sample drying at the 20 LC room temperature, the strengthening effect was still neglectable at both 66% and 33% water content level. According to the Fig. 5, the water evaporating rate of sample drying at the 20 LC room temperature gradually decreased while the rate kept constantly in the 40 LC oven drying condition. Unlike xanthan gum performance in the sample with 100% and 66% water content which did not exhibit its gel-like property, xanthan biopolymer with 33% water content presented its viscosity and bonding property. After finishing the direct shear test, it can be observed that surface of the sample was dry and solid while inner part was still moist. Thus, it can be supposed that when sample drying at the 20 LC room temperature, the external part of the sample was exposed on the air-dry condition and the xanthan gum biopolymer would quickly show its crystallization and cementation effect. This lead to the distribution of biopolymer cross-link mainly located on the sample external. However, as the outer surface of the sample was dry and solid, this would also slow down the cementation process in the inner part of samples. So it was still moist weak-link gel inside the sample. During the shearing, the location of the shear plane was the internal part of the sample which was weak and uncross-linked and finally showed the limited effect of xanthan gum biopolymer in the soil.

As a comparison, when samples were cured in the 40 LC oven, the linear water evaporation rate illustrated that the cementation process in the external and inner is simultaneous. What is more, for the relatively high temperature (40 LC) drying, the increase of temperature would accelerate the molecular mobility and increased the interaction between biopolymer sand particles. Thus, it showed the better effect on the soil strength for drying at the 40 LC room temperature.

4.2.2. Dry condition

However, according to the gel property, with continual evapora-tion, gel will finally form the thin film and then to the solid which has different adhesive property. This may lead to the change of biopolymer performances in the sand. Fig. 6 shows under the fully dried condition, the shear strength of the 0.25% and 0.5% biopoly-mer treated soil after different drying. It is obvious that there is a great improvement of peak shear stress of both 0.25% and 0.5% biopolymer treated soil. For example, when the vertical stress is 100 kPa, the strength of 0.25% concentration biopolymers treated soil under 40 LC oven fully dry condition varies from 180 kPa to 210 kPa, more than drying at the 20 LC room temperature which ranges from 135 kPa to 150 kPa, far more than the 100% water con-tent condition. However, unlike the other conditions, the triplicate test results under fully dried condition showed their huge variability.

As pointed out in the previous section, the biopolymer solution started to bond the soil particles together, there was a consistent increase in soil strength with the water content decrease in the soil after drying. At this stage, the bonding force between particles keep increasing. The gel here was branched cluster but behaved as discrete species. The removal of water resulted in additional crosslink and strengthen the gel network. This finally led to the dry biopolymer treated soil cohesion and shear strength increase. Additionally, the higher temperature would activate biopolymer molecules and increase their particles kinetic energy [27]. Thus, the samples drying in the 40 LC oven had higher strength than that drying at the 20 LC room temperature. Nevertheless, with the con-tinuous evaporation of water, gel gradually spread into the concen-trated gel and then became the thin layer and shrank. During this process, the mobility of biopolymer gradually decreased until to the zero [26]. Besides, as the biopolymer was still flowing gel in the soil, the uncontinuous hydrogels would occupy the soil void
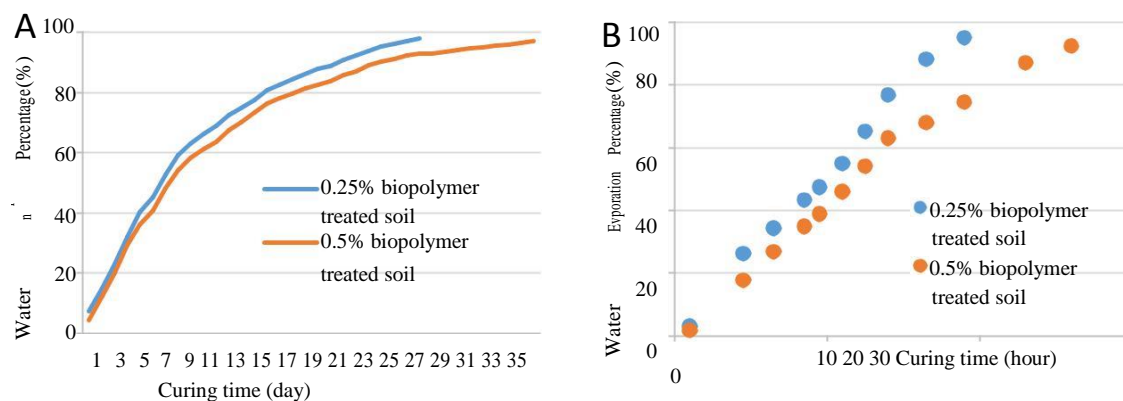

Fig. 5. Water evaporation percentage of xanthan gum biopolymer treated soil under different dring condition (A: Drying in the 20 LC room temperature; B: Drying in the 40 LC oven).
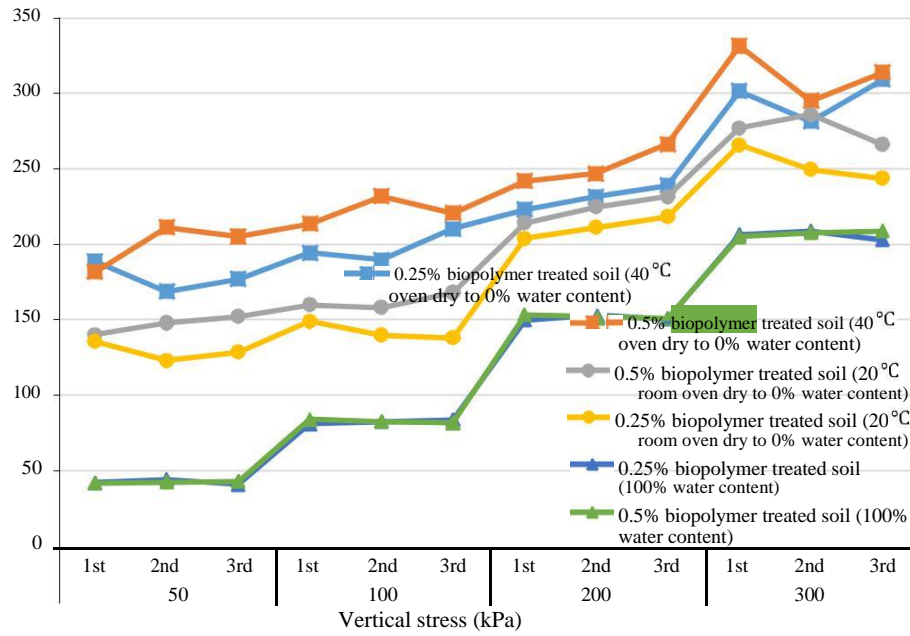
Fig. 6. Biopolymer treated soil strength under fully dry condition after drying.
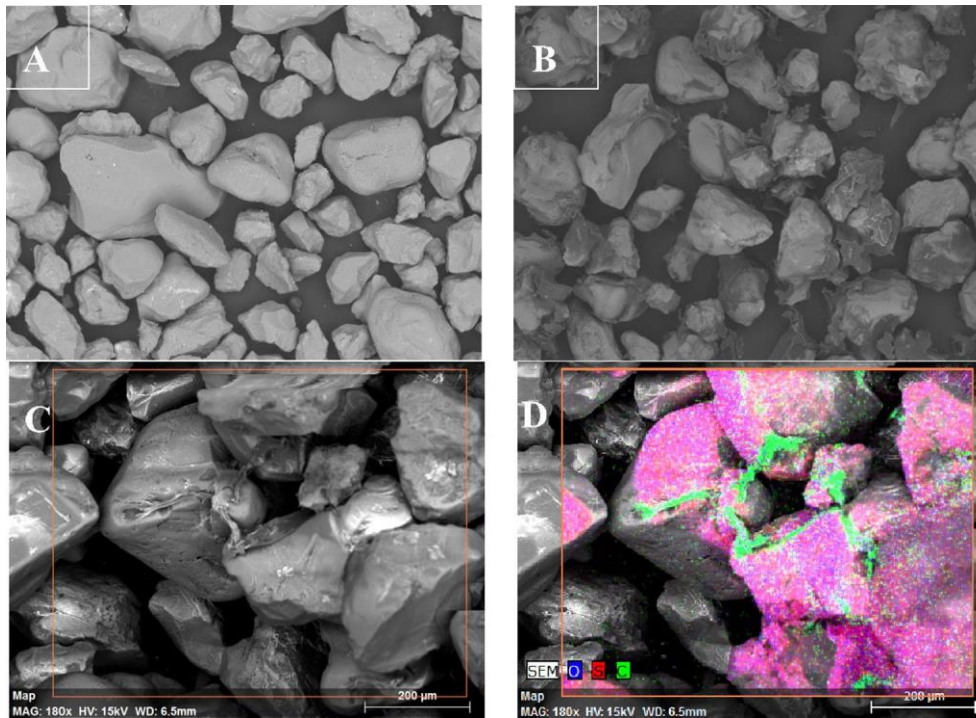

Fig. 7. SEM images of biopolymer treated soil. (A) Clean sand sample. (B) Xanthan gum biopolymer treated sand. (C) Sand aggregation connected by the xanthan gum biopolymer. (D) Chemical element distribution map.

inhomogeneous and finally formed the biopolymer film in the soil. Once the thin film attached to the soil particle cannot shrink in each direction, the film was fixed and unable to present fluidity. Bonding stress developed on the surface of the soil. With continu-ally shrinking, the crack was generated to form the fracture surface [28]. Thus some surface connections between the soil particles and

biopolymer became brittle. As the inhomogeneous distribution of biopolymer film developing in the soil to bond individual soil par-ticle to form the soil aggregation, the bonding strength between the soil particles also presented huge variability. Some condensed gel associated with soil tightly while other parts are brittle, after applying horizontal force, some aggregations (Fig. 7C and D) were

easily parted which lead to the variability of shear stress. In gen-eral, there was still a considerable increase in soil strength, but this increase is unpredictable and inconsistent.

4.3. Microscopic behaviour

The SEM images of biopolymer treated soil are presented in Fig. 7A–D. In the Fig. 7A, for the clean sand sample, the sand con-tained irregular and independent particles [29]. After adding biopolymers and drying, the xanthan gum polymers adsorbed and gathered around soil particles which can be seen in Fig. 7B. Besides, some polymers acted as bridges to connect the individual sand particles together, small particles aggregated to form a larger one (Fig. 7C). By using chemical element analysis method, for sand with biopolymer, signal of C element was detected (the main com-position of xanthan gum biopolymer), thus we conducted that xan-than gum were distributed and connected around the sand (SiO_2) in Fig. 7D. These connection bridges thus provided cohesion in the sand [20].

Based on the microscopic observation of biopolymers treated soil, the schematic diagram of sand motion condition under shear-ing is hypothesized in Fig. 8). For the clean sand sample, as there was almost no cohesion, the shear strength was mainly caused by the soil movement resistance at the particles contacted surface in Fig. 8A, B [30]. For the biopolymers treated sand, biopolymers tan-gled with sand particles to form the matrix. As mentioned in the previous section, the bonding property of the biopolymer resulted in the increase of sand cohesion. In addition, small scattered sand connected with the biopolymers and formed the larger aggregation which increased rotational resistance (Fig. 8C, D). These effects increased biopolymer treated sand strength [31]. However, the inconsistent improvement of strength means the bonding condi-tion and pattern varied under the dry condition (Fig. 8E, F). With the continuous increase of water evaporation, biopolymer precipi-tate and shrank, different bridge forms between sand particles. Thus the bonding strength between each sand particle was differ-ent. Furthermore, the interaction of biopolymers and sand particles would form the different size and shapes of the matrix. There were many forms of rotation and movement during the shear of these matrixs (Fig. 8C, D). These results indicated that under dry condi-tion, the biopolymer bonded sands form a heterogeneous connec-tion and resulted in the variability of shear strength.

4.4. Bonding property of biopolymer

In the direct shear test, the adding of biopolymer indeed improved the soil strength after drying over the time. In the begin-ning, biopolymers did not present their soil stabilisation effect due to the high water content. When water content decreased in the soil, the biopolymer bonding property gradually appeared. This lead to both friction and cohesion enhan cement between the soil particles and finally increased the soil strength. As the existence of the biopolymer is the key factor in influencing soil structure, while bonding property varied from the drying, thus it is important to discuss the biopolymer bonding property performance with differ-ent water content after drying.

Fig. 9 presents the bonding stress of different concentrations of biopolymer gel after different drying condition to the different water contents respectively. Like the shear strength in the soil, the adhesive property of the biopolymer showed an increasing trend after drying at the different water contents overall. When the water content stayed at high levels (100% and 66%), both 0.25% and 0.5% concentration biopolymer adhesive stress were at a very low value. The content of xanthan biopolymer particles was extremely low in the water that most water exhibited its fluid property rather than the gel property. This resulted in no signifi-cant improvement in soil cohesion and shear strength. However, with an increase in the drying time, the water kept evaporating and the adhesive hardened. Molecular interactions would bond the particles closely which lead to the adhesive stress increase [32]. Compared to the high water content, after drying (water con-tent from 66% to 33%), adhesive stress increased about two times. Higher biopolymer concentration means there were more molecu-lar attractions between the contacting surfaces. So the 0.5% biopolymer adhesive stress is higher than the 0.25%. It worth not-ing there was also an increase for the xanthan gum biopolymer drying in the 20 LC room temperature to the 33% water content. This can verify the biopolymer crystallize and cement with sand during this condition and the results are also in line with the pre-vious supposition. Higher adhesive stress means higher cohesion between the soil particles which can be found in Table 1. Finally, when most of the water had evaporated, there were massive increases in the adhesive stress. However, the biopolymer also shrank and became brittle. The contacted area decreased and cracks happened in the weakest place which lead to the variability
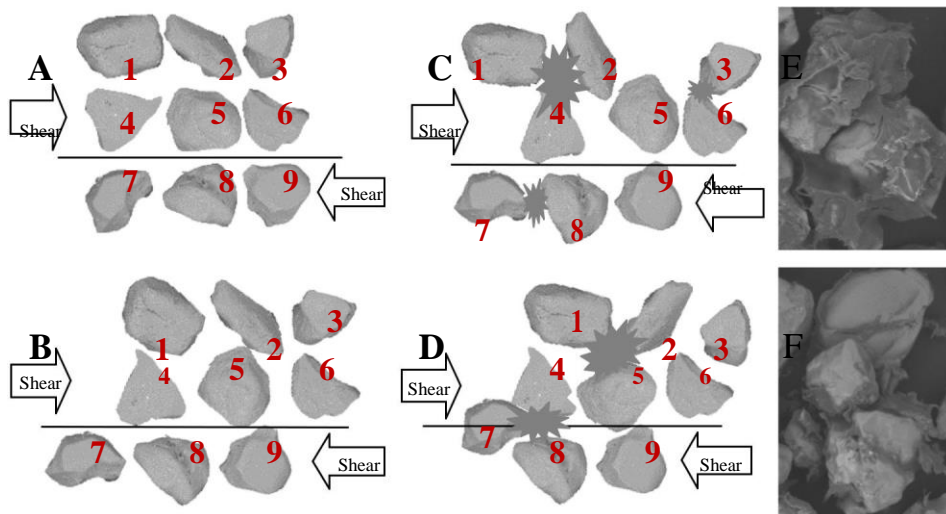

Fig. 8. Schematic diagram of sands motion condition under shearing. (A) The distribution of clean sand before shearing. (B) The distribution and movement of clean sand under shearing. (C) The aggregation and distribution of biopolymer treated sand before shearing. (D) The distribution and movement of biopolymer treated sand during shearing. (E) and (F) the different connection and aggregation of biopolymer treated sand.
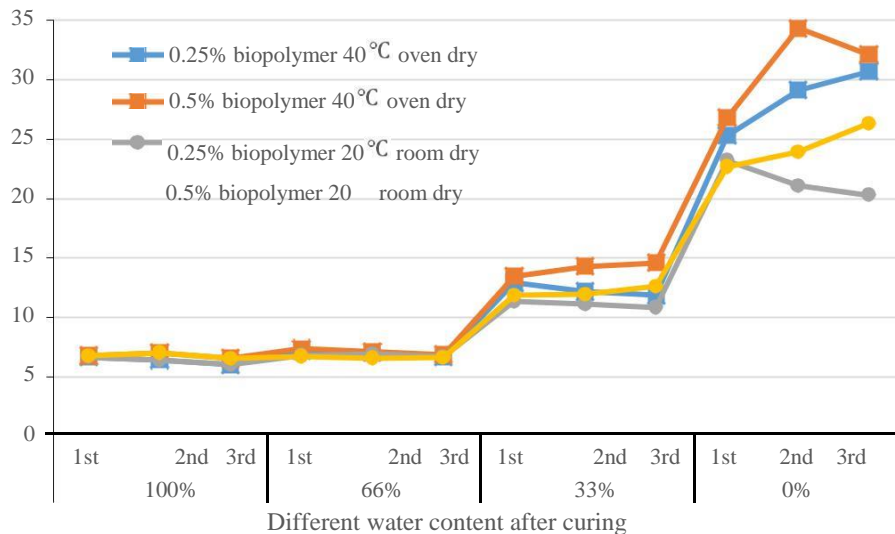
Fig. 9. Bonding stress of different concentration biopolymer gel after drying.

of adhesive stress. These results are also consistent with the direct shear results in Fig. 6.

5. Conclusion

This study carried out a series of laboratory tests to explore the influence of drying effect to the xanthan gum biopolymer treated sand. At the initial state (before the drying), the shear strength of xanthan gum biopolymer treated sand samples and clean sand samples are similar which indicates biopolymer had little effect at the initial stage, As the cross-link biopolymer was so weak and can be easily broken, the fluid property still played the prominent role compared to its adhesive bonding property. The adding of xanthan gum did not show any obvious effect on the soil strength. With continuous evaporation of water (40 LC oven drying to 33% water content), bonding property of the biopolymer gradually appeared which lead to the increase of the soil shear strength. Higher biopolymer content samples presents better strengthening effect. Compared to the samples drying in the 40 LC oven condition, the peak shear strength of biopoly-mer treated soil drying in the 20 LC room temperature condition was still similar to the clean sand samples. Because when sample drying in the 20 LC room temperature condition, the outer surface of the sample was cemented and crystallised by the xanthan gum biopolymer while the inner part was still moist and weak cross-link by the solution, which lead to the weak shear strength. When the water had completely evaporated, the strengthening effect of xanthan biopolymer reaches maximum. But the biopolymers shrank and became brittle which lead to a variability of cohesion of soil strength.

The scanning electron microscope images of samples showed the inter-particle tangle between biopolymers and soil. The sche-matic diagram of sand motion was proposed to illustrate the biopolymer treated sand shear performance of sand and gave the further explanation of variability of biopolymer treated sand strength. These results indicated that under dry condition, the biopolymer bonded sands form a heterogeneous connection and resulted in the variability of shear strength.

In addition, the bonding property of biopolymers was also tested and discussed. Biopolymer bonding stress increased signifi-cantly after drying and became unstable under fully dry condition. These results are all consistent with the direct shear test results.

Conflicts of interest

None.

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