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Effects of Non-Newtonian Pore Fluids on Soil Shear Strength

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ABSTRACT

This study explores the effects of non-Newtonian pore fluids on the shear strength of soils. Water is considered the dominant pore fluid in most geotechnical problems (e.g., slope stability and liquefaction). Given water's Newtonian behavior as a fluid, less attention has been given to its rheological properties' and how changing such properties impacts the mechanical behavior of soils. However, other pore fluids that have non-Newtonian behavior are of increasing interest nowadays. Among these non-Newtonian fluids, eco-friendly biopolymers (e.g., Xanthan Gum "XG") gained particular attention as a prospective additive to replace the traditional soil improvement techniques, e.g., cement and lime. In this study, we investigate the impact of these non-Newtonian fluids on the shear strength of coarse-grained media. We explicitly consider the effect of XG mixed at different percentages (0.5%, 1%, and 1.5% with respect to the dry mass) on the soil strength determined using consolidated undrained triaxial (ICU) tests. The rheological properties of XG-water mixtures at each XG percentage were evaluated using Brookfield DVNext Rheometer. The results showed that mixing smooth granular material with XG gel with up to 1% XG concentration improved the shear strength of the tested granular soil. However, using a higher amount of XG negatively affected the shear strength.

Keywords: shear strength, soil improvement, biopolymer, xanthan gum, rheological properties.

1 INTRODUCTION

Constructing resilient communities motivate geotechnical engineers to handle weak soils. In order to construct different structures on weak soils, engineers need to implement some soil improvement techniques, for example, cement or lime improvement (Chang et al., 2015b). However, using these materials for soil improvement has been related to several environmental issues caused by cement dust and emissions of CO_2 caused by calcination (Bremner & Eng, 2001; Meo, 2004). Therefore, research in the past few years has been focused on stabilizing soils using eco-friendly additives; one of these eco-friendly materials is biopolymers, owing to their cost efficiency and availability.

The main objective of this paper is to assess the effect of one non-Newtonian type of biopolymer (Xanthan Gum) with different percentages on the shear strength of saturated granular materials. In this paper, a literature review on the effect of different types of non-Newtonian biopolymers with different percentages on the shear strength of soils is presented. An experimental program is designed to study the impact of different XG percentages on soil strength, obtained using Consolidated Undrained (ICU) triaxial tests. The results are finally presented and discussed in terms of the effective shear strength parameters.

2 BACKGROUND

The improvement in the unconfined compressive strength (UCS) of different soils upon mixing with the non-Newtonian Xanthan Gum has been widely studied (e.g., Chang et al., 2015a), as shown in Figure

1. Xanthan gum (XG) significantly increased the compressive strength of sand and clay after 28 days of air curing (Chang et al., 2015a). The improvement for clay was found to be higher than that for sand because of the direct bond between XG chains and clay particles through cation bridging and the hydrogen bonds between the charged clay particles and both hydroxyl (-OH) and carboxylic acid (-COOH) groups of XG (Nugent et al., 2009). Furthermore, xanthan gum improved the shear strength of sandy clay more than clayey soils, which can be attributed to the friction component of the coarse particles (i.e., sand) that enhanced the strength of the soil. A comparison between the improvement of 1% XG and 10% cement on the UCS of sandy clay showed that 1% of XG improved the shear strength of this soil higher than 10% of the cement (Chang et al., 2015a).

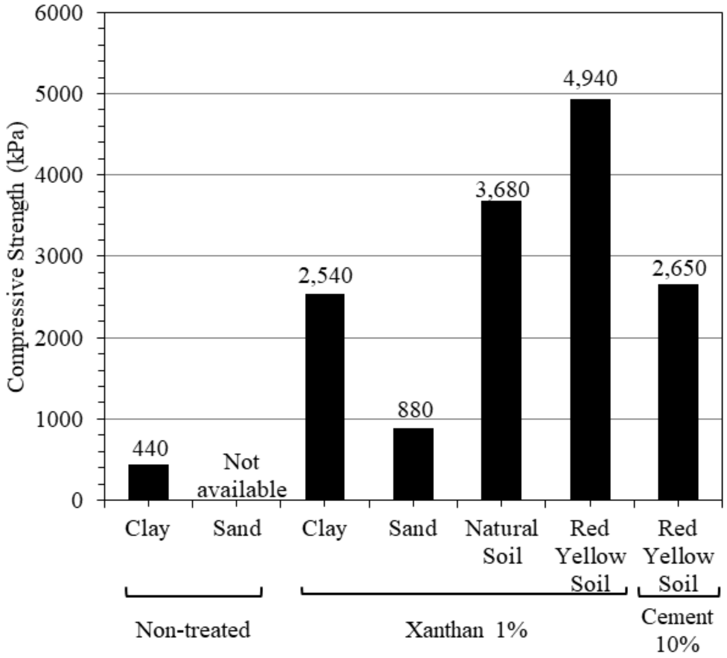

Figure 1. *Compressive strength of different soil types mixed with 1% Xanthan gum after 28 days of air curing (Chang et al., 2015a).*

Other non-Newtonian biopolymers have also been considered for soil improvement. The effect of Agar gum on the shear strength of sand was studied using unconsolidated undrained triaxial compression tests, as shown in Table 1. The triaxial results showed an increase in the cohesion intercept and a decrease in the friction angle with the increase in the Agar percentage. The increase in the cohesion intercept might be attributed to the accumulation of biopolymer inside the pores of the sand, which in turn bridges between particles (Khatami & O'Kelly, 2013). The increase in the cohesion intercept can be further increased by adding positively charged starches (e.g., Starpol 600 or Starpol 136), which attach to the negatively charged biopolymer and increase soil cohesion. On the other hand, the decrease in the friction angle is attributed to the lubricating effect of biopolymer, which makes sliding between the grains of the granular material easier (Khatami & O'Kelly, 2013).

Table 1. *Shear Strength parameters for sand with different percentages of agar and starches (Khatami & O'Kelly, 2013).*

Conditions	Method			
	Nonlinear optimization		Linear least squares	
	c' (kPa)	ϕ' (degree)	c' (kPa)	ϕ' (degree)
Untreated sand	0	32.3	0	33.1
1% agar	62	24.7	49	25.4
2% agar	111	25.6	105	26.4
4% agar	190	26.3	222	23.6
1% agar and 0.5% Starpol 600	187	17.5	187	17.5
1% agar and 1% Starpol 136	240	17.6	245	17.4

3 MATERIAL

Glass beads were utilized as a reference material to represent granular media in this study. Glass beads were preferred over sand due to the ability to control their gradation of the material, allowing for any desired gradation. In addition, the spherical and smooth nature of glass beads makes them an ideal reference material. Rounded glass beads of various sizes were obtained from Potters, MP Biomedicals, and Thermo Fisher Scientific. Using different sizes, we prepared a well-graded mix and used it for triaxial testing. The grain size distribution curve for the glass beads used in the experimental program is shown in Figure 2, and grain-size characteristics are presented in Table 2. The classification of the glass beads used in this study based on the unified soil classification system (USCS) is well-graded sand (i.e., SW) (ASTM D2487-17).

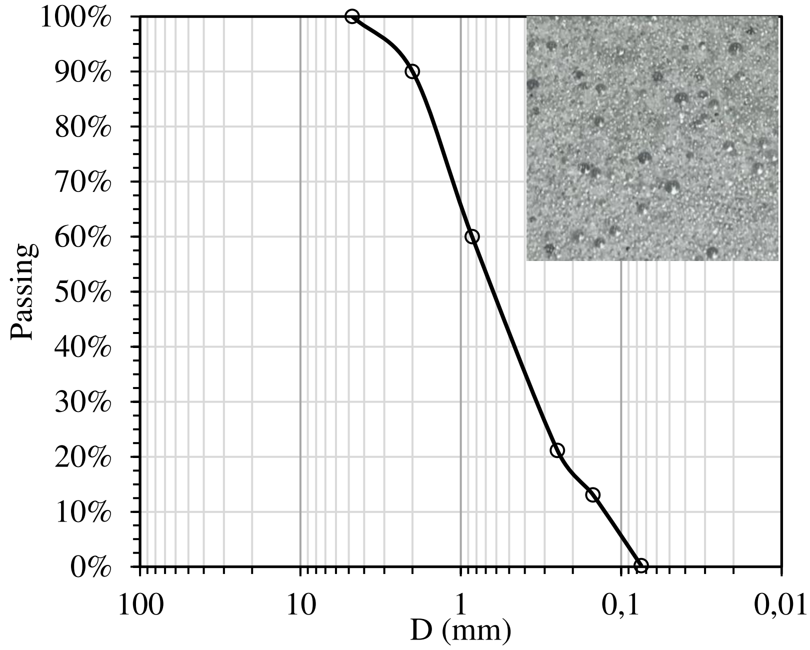

Figure 2. *Grain size distribution of the used glass beads.*

Table 2. *Glass beads properties*

Parameter	Value
Effective Diameter *(D_{10}*, mm)	0.12
Coefficient of uniformity *(C_u*)	7.08
Coefficient of curvature *(C_c*)	1.13
Maximum void ratio *(e_{max}*)	0.47
Minimum void ratio *(e_{min}*)	0.30
Specific Gravity *(G*s)	2.50

Xanthan gum (XG) from Judee's vendor, which is used in this study, is an anionic polysaccharides material produced by the fermentation of glucose or sucrose by a bacterium called "Xanthomonas Campestris" (Rosalam & England, 2006; Davidson, 1980). The viscosity degradation of the Xanthan Gum is highly dependent on the shear rate, a behavior known as "pseudo-plasticity" (Casas et al., 2000); thus, this XG is non-Newtonian.

4 EXPERIMENTAL PROGRAM

In order to study the effect of the XG percentages on the shear strength parameters of biopolymer-treated soil specimens, isotropic consolidated undrained triaxial compression (ICU) tests (ASTM D 4767-11) were conducted. All triaxial specimens had a diameter and height of about 71 mm and 132 mm, respectively, and they were prepared at an initial relative density of about 35% using the undercompaction method (Ladd, 1978). The saturation process of each of these specimens was performed using the backpressure saturation method to achieve a minimum pore water pressure parameter B of 0.95; this process took from 4 to 7 days depending on the XG dosage in the sample (higher XG dosage needs more time for saturation), using a back pressure up to 1500 kPa. It is important to allow sufficient time during the saturation stage to ensure complete saturation of xanthan gum. This ensures that the biopolymer is fully hydrated and prevents it from absorbing any moisture present in the sample, thereby promoting a consistent distribution of pore fluid within the material.

The failure criteria for granular materials can be defined by the maximum deviatoric stress, Skempton's pore water pressure $\bar{A}$ = 0, maximum principal stress ratio, or at a certain deviatoric strain, for example, 10% (Brandon et al., 2006). The range of shear strength parameters obtained using those failure criteria are narrow; hence, those failure criteria are comparable (Brandon et al., 2006). The peak deviatoric stress was not reached for most of the samples with XG biopolymers. Therefore, the maximum principal stress ratio, defined as the ratio between the major and the minor effective principal stresses, was used as a failure criterion for xanthan gum-treated specimens in this study. To ensure consistency in the results and facilitate meaningful comparisons, the maximum principal stress ratio was also utilized for the clean glass beads.

In this study, the pore fluid used was not the conventional fluid used in soil mechanics, i.e., water. Therefore, investigating the rheological properties, specifically viscosity, of this fluid was deemed important. The concentration and type of biopolymer used in the fluid can significantly affect its viscosity. Previous research suggests that the viscosity of these materials has a significant impact on shear strength *(Khatami & O'Kelly, 2013)*. The rheological properties of the XG solution were measured using a Brookfield DVNext LV rheometer, following ASTM D 2556-14, as shown in Figure 3. Two sets of rheological tests were performed, the first for XG mixed with the initial water content of the triaxial specimens, i.e., 10% of the dry soil mass, and the second set for XG mixed with the estimated water content before shearing, i.e., after XG being fully hydrated and the specimen being fully saturated and consolidated. Three different XG dosages were used in this study, 0.5%, 1%, and 1.5 with respect to the dry granular material weight. The rheometer test results show a non-Newtonian shear thinning behavior for all tested XG solutions over the tested shearing rates (i.e., the viscosity of these solutions decreased with the increase of the shearing rate). The viscosities at a shearing rate equal to 1 s^{-1} (i.e., log1 = zero) for all tested XG solutions are presented in Table 3. This viscosity increased for the solution prepared using the initial water content (i.e., 10%) from 66069 cP to 288403 cP (i.e., more than 336% increase) with an increase of XG dosage from 0.5% to 1.5% with respect to the dry glass beads weight. For the solutions prepared at the water content before the shearing stage of the triaxial test, this increase was about 307% (Table 3).

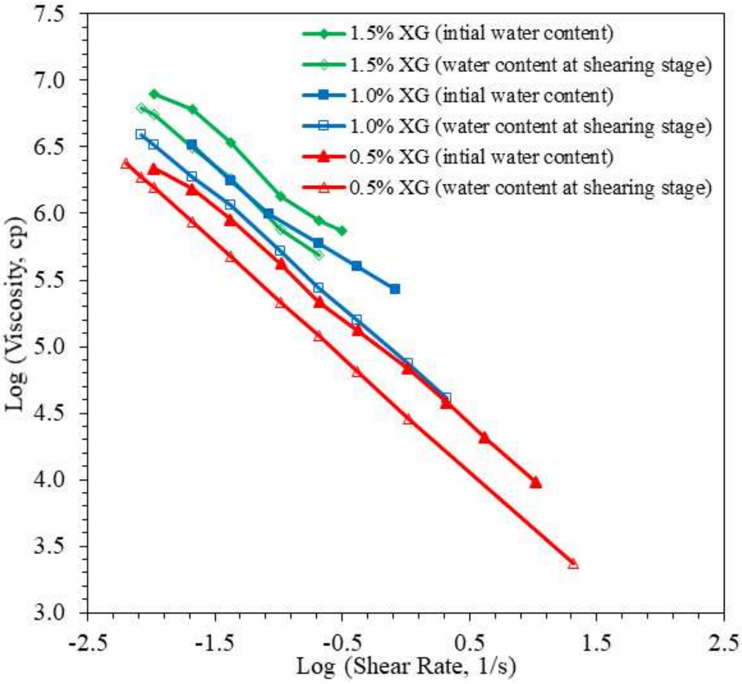

Figure 3. *Rheological properties of XG used in this study.*

Table 3: *Tested xanthan gum (XG) viscosity at strain rate = 1s^{-1}*

XG Dosage*	Viscosity (log (cP))	
	Initial Water Content Condition	Water Content at Shearing Stage
0.5%	4.82	4.50
1.0%	5.43	4.89
1.5%	5.46	5.11

* All percentages are with respect to the dry soil weight

5 ICU TRIAXIAL RESULTS

The triaxial test results of the well-graded clean glass beads are presented in Figure 4. The sudden drop in the deviatoric stress and sudden increase in the excess pore water pressure after initial shearing in Figure 4 (dash curves) are associated with the stick-slip behavior of the glass beads (Cui et al., 2017). For clarity, the solid curves shown in Figure 4 were constructed by ignoring this abrupt drop in the deviatoric stress (Figure 4a) and the corresponding increase in the excess pore water pressure (Figure 4b).

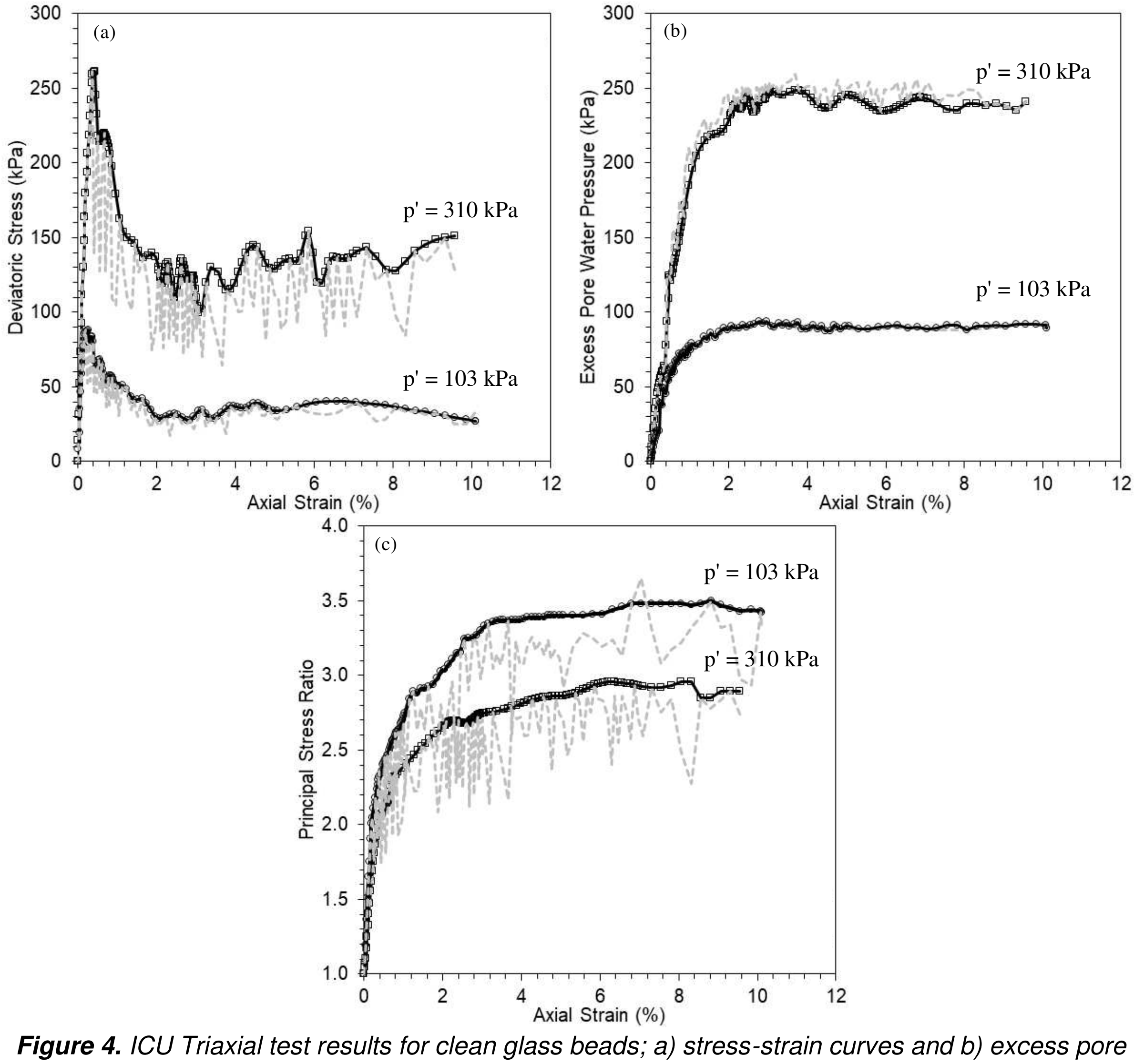

Figure 4. *ICU Triaxial test results for clean glass beads; a) stress-strain curves and b) excess pore water pressure during shearing.*

The triaxial test results on saturated specimens mixed with 0.5%, 1%, and 1.5% of XG with respect to the dry glass beads' weight are presented in Figures 5 and 6. At confining stress of 103 kPa (Figure 5), the stress-strain behavior of granular material changed from shear softening to hardening after being mixed with 0.5% XG or 1.0% XG (Figure 5). At higher confining stress (i.e., 310 kPa in Figure 6), the same observation was noticed for the soil being mixed with up to 1%XG (Figure 6). However, when this granular material was mixed with 1.5% XG, the material shearing behavior did not change, i.e., it remained softening as the untreated specimen (Figure 6). Moreover, the maximum principal stress ratio for the clean glass beads was higher than that for glass beads treated with XG; this was observed for all confining stresses, as appears in Figures 5-c and 6-c. A summary of the ICU triaxial test results is presented in Table 4, while the shear strength parameters for these soils are shown in Table 5.

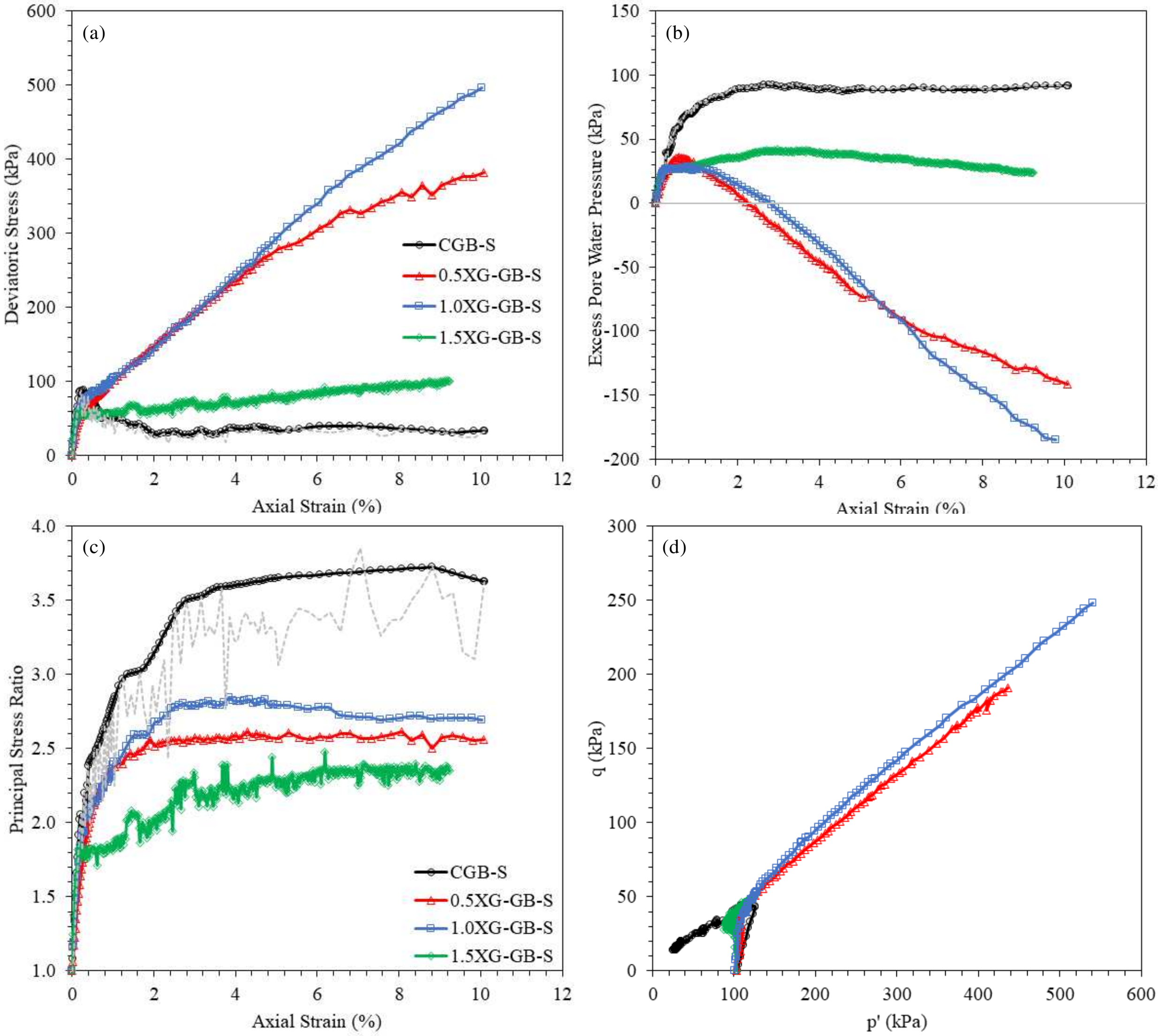

Figure 5. *ICU Triaxial test results ($\sigma_{3'con}$ = 103 kPa); a) stress-strain curves, b) excess pore water pressure dissipation, c) principal stress ratio, and d) p'-q curves.*

The friction angle of the clean glass beads was relatively low (i.e., 31.7°) because of their roundness and smooth surface. However, adding xanthan gum to the glass beads further decreased the friction angle by up to 21% (~6.7°) with the incorporation of up to 1% XG and up to 27% (8.5°) with the use of 1.5% XG. This can be attributed to the lubrication effect of the biopolymer, which coats the granular media particles and facilitates easier sliding between them. On the other hand, the cohesion intercept of the specimens treated with 0.5% XG and 1% XG increased by about 7 kPa and about 4 kPa, respectively, because XG chains connect glass bead particles with a viscous bond. However, no cohesion intercept was developed for the sample treated with 1.5% XG, probably due to having a bigger space between particles. In summary, it appears that a 0.5% XG improved the shear strength parameters better than 1.0% and 1.5% XG; thus, we can conclude that 0.5% XG is the optimum percentage for this soil condition.

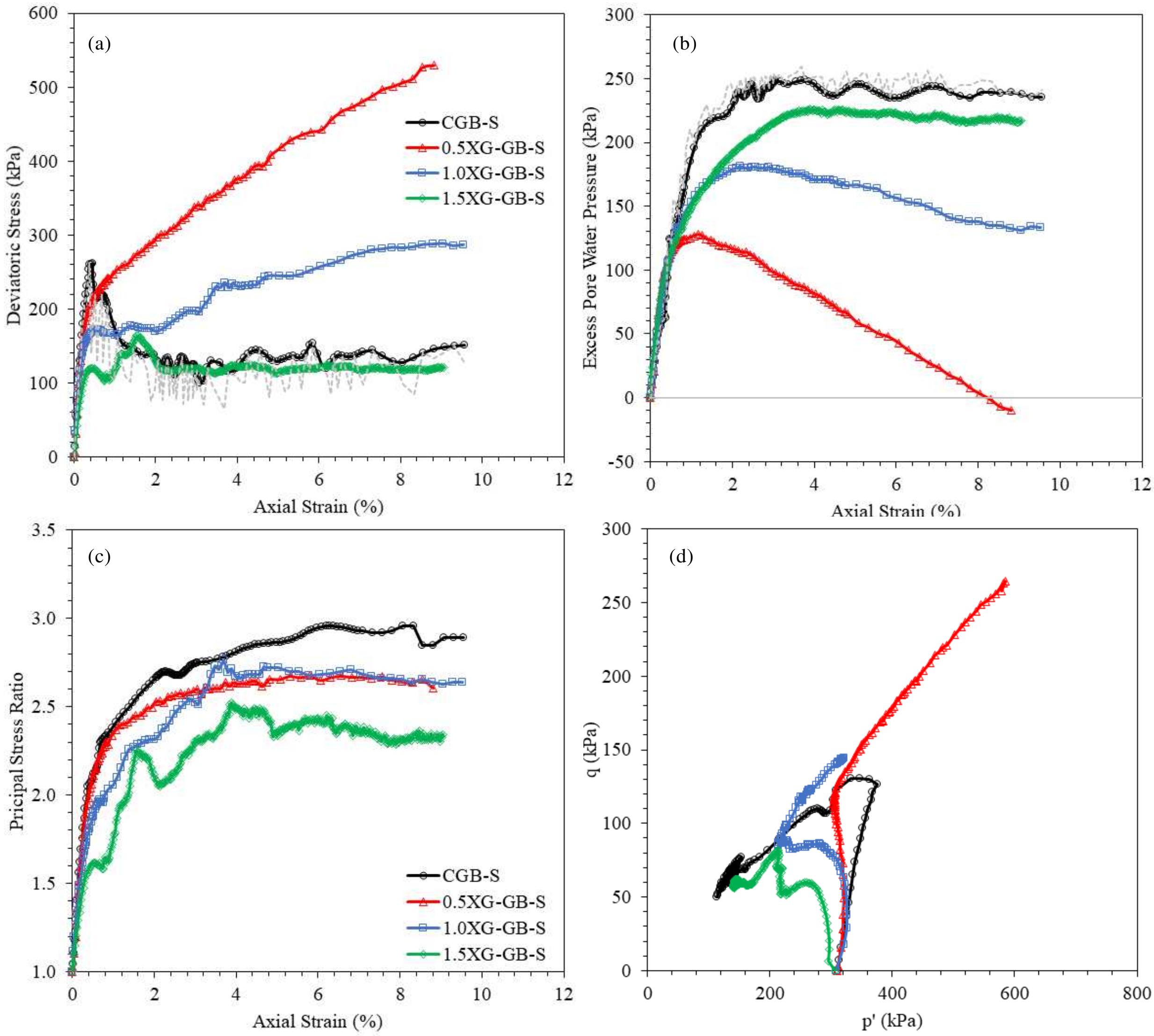

Figure 6. *ICU Triaxial test results ($\sigma_{3'con}$ = 310 kPa); a) stress-strain curves, b) excess pore water pressure dissipation, c) principal stress ratio, and d) p'-q curves.*

Table 4. *Summary of failure strains based on the maximum stress ratio and the corresponding deviatoric stress for the conducted ICU triaxial tests, Dr_i = 35%, e_o = 0.41, w_i = 10%.*

Confining Stress, kPa	XG dosage, %	Void ratio before shearing	Final Water Content, %	Max. Stress Ratio	Failure Strain, %	Deviatoric stress at the failure strain, kPa	Excess Pore water at the failure strain, kPa
103	Zero	0.40	16.4	3.6	3.9	37.1	88.9
	0.5	0.41	17.1	2.6	4.3	250.7	-51.9
	1.0	0.41	17.4	2.7	2.0	145.6	14.0
	1.5	0.41	17.6	2.4	7.1	92.1	31.6
310	Zero	0.40	16.4	2.8	3.6	126.8	247.4
	0.5	0.40	17.1	2.6	2.6	320.7	107.4
	1.0	0.40	17.4	2.6	3.3	211.7	177
	1.5	0.40	17.6	2.3	3.3	116.1	220.6

Table 5. *Summary of friction angle for the conducted ICU triaxial tests, Dr_i = 35% and w_i = 10%*.*

XG Dosage, %	Effective Friction, Degrees	Cohesion, kPa
0.0	31.7	0
0.5	25.0	6.9
1.0	25.4	3.9
1.5	23.2	0

6 CONCLUSION

Biopolymers are considered a promising alternative for soil improvement to limit the environmental problems resulting from traditional methods, e.g., cement stabilization. Xanthan gum (XG), as an example of these biopolymers, was used in this study. The rheological properties performed on XG solution showed that these solutions have a shear thinning behavior, and the viscosity at a strain rate of 1 s^{-1} increased with increasing XG percentage. Moreover, the ICU triaxial results showed that The incorporation of xanthan gum into smooth sphere glass beads resulted in a reduction of their friction angle due to the biopolymer's lubrication effect. Moreover, the cohesion intercept for the granular material samples mixed with 0.5%XG was higher than other percentages (1% and 1.5%) used in this study. Further, the stress-strain behavior of the granular material used in this study changed from shear softening to hardening for most of the tested biopolymer-treated soils at two different confining stresses. Also, the ICU triaxial results showed that 0.5% XG performed better than 1.0% and 1.5% XG when mixed with smooth glass beads.

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REFERENCES

ASTM Standard D4767, 2011 (2020), "Standard Test Method for Consolidated Undrained Triaxial Compression Test for Cohesive Soils" ASTM International, DOI: 10.1520/D4767-11R20, www.astm.org.

ASTM Standard D2556, 2014 (2018), "Standard Test Method for Apparent Viscosity of Adhesives Having Shear-Rate-Dependent Flow Properties Using Rotational Viscometry" ASTM International, DOI: 10.1520/D2556-14R18, www.astm.org.

ASTM Standard D2487, 2017 (2020), "Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System)" ASTM International, DOI: 10.1520/D2487-17E01, www.astm.org.

BRANDON, T. L., ROSE, A. T. & DUNCAN, J. M. 2006. Drained and undrained strength interpretation for low-plasticity silts. *Journal of Geotechnical and Geoenvironmental Engineering,* 132**,** 250-257.

BREMNER, T. & ENG, P. Environmental aspects of concrete: problems and solutions. All-Russian Conference on Concrete and Reinforced Concrete, 2001.

CASAS, J., SANTOS, V. & GARCıA-OCHOA, F. 2000. Xanthan gum production under several operational conditions: molecular structure and rheological properties☆. *Enzyme and microbial technology,* 26**,** 282-291.

CHANG, I., IM, J., PRASIDHI, A. K. & CHO, G.-C. 2015a. Effects of Xanthan gum biopolymer on soil strengthening. *Construction and Building Materials,* 74**,** 65-72.

CHANG, I., PRASIDHI, A. K., IM, J. & CHO, G.-C. 2015b. Soil strengthening using thermo-gelation biopolymers. *Construction and Building Materials,* 77**,** 430-438.

CUI, D., WU, W., XIANG, W., DOANH, T., CHEN, Q., WANG, S., LIU, Q. & WANG, J. 2017. Stick-slip behaviours of dry glass beads in triaxial compression. *Granular Matter,* 19**,** 1-18.

DAVIDSON, R. L. 1980. *Handbook of water-soluble gums and resins,* New York, McGraw-Hill.

KHATAMI, H. R. & O'KELLY, B. C. 2013. Improving mechanical properties of sand using biopolymers. *Journal of Geotechnical and Geoenvironmental Engineering,* 139**,** 1402-1406.

LADD, R. 1978. Preparing test specimens using undercompaction. *Geotechnical testing journal,* 1**,** 16-23.

MEO, S. A. 2004. Health hazards of cement dust. *Saudi medical journal,* 25**,** 1153-1159.

NUGENT, R. A., ZHANG, G. & GAMBRELL, R. P. 2009. Effect of exopolymers on the liquid limit of clays and its engineering implications. *Transportation Research Record,* 2101**,** 34-43.

ROSALAM, S. & ENGLAND, R. 2006. Review of xanthan gum production from unmodified starches by Xanthomonas comprestris sp. *Enzyme and Microbial Technology,* 39**,** 197-207.

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