**Geomechanics and Engineering**, *Vol. 22, No. 5 (2020) 441-448*
DOI: https://doi.org/10.12989/gae.2020.22.5.441


# Fall-cone testing of different size/shape sands treated with a biopolymer

Ali Firat Cabalar*[1] and Suleyman Demir[2a]

[1]*Department of Civil Engineering, University of Gaziantep, Gaziantep 27310, Turkey*
[2]*Department of Civil Engineering, Kilis 7 Aralik University, Kilis 79000, Turkey*

*(Received April 24, 2019, Revised July 23, 2020, Accepted August 2, 2020)*

**Abstract.** This paper presents a study on the undrained shear strength ($s_u$) of various sands treated with a biopolymer by employing an extensive series of laboratory fall-cone penetration values covered a range of about 15 mm to 25 mm. In the tests, two sizes (0.15 mm-0.30 mm, and 1.0 mm-2.0 mm) and shapes (rounded, angular) of sand grains, Xanthan gum (XG), and distilled water were used. The XG biopolymer in 0.0%, 1.0%, 2.0%, and 3.0% by dry weight were mixed separately with four different sands, and water. The tests results obtained at the same water content revealed an increase in the su values at different levels with an increase in the XG content. Treating the sands with the XG biopolymer addition was concluded to have a greater efficacy on finer and more angular grains than coarser and more rounded grains in the samples. Overall, the present study indicates that different amount of the XG biopolymer has an important potential to be utilized for increasing the $s_u$ values of samples with various size/shape of sand grains and water content.

**Keywords:** fall-cone; xanthan gum; sand; size; shape

## 1. Introduction

Soil stabilization techniques improve various geotechnical engineering properties including strength, compressibility, permeability, and plasticity by means of electrical, biological, chemical, and mechanical ways. Soil stabilization still remains as one of the most considerable challenges in geotechnical engineering, particularly due to the developments of new materials, although the basic principles of soil stabilization namely; drainage, reinforcement, densification, and cementation, have not changed for about last 5000 years (Mitchell 1981, Terashi and Juran 2000, Schaefer *et al.* 2012). Soil stabilization by means of chemical materials (traditional and non-traditional materials) seems to be one of the most commonly utilized techniques. Cement, a traditional chemical material, was first introduced as a stabilizer in early 1900s in Florida, USA. It has been the most widely used chemical stabilizer in different geotechnical engineering applications since then, because of its easily availability, simple application, and low cost.

Numerous investigations reporting improvement in strength, compressibility, permeability and plasticity of problematic soils have been studied on various soil-cement mixtures (Rafalko *et al.* 2007, Saadeldin and Siddiqua 2013, Shrestha and Al-Tabbaa 2012, Pan *et al.* 2019). Traditional materials including cement basically depend on pozzolanic chemical reactions and exchanging cations in order to make a stabilization in a soil (Abu-Farsakh *et al.* 2015). Actually, main environmental problems associated with cement manufacture are consumption of natural materials and energy use as well as emissions to atmosphere. Hence, such environmental issues have recently increased the interests on studies in non-traditional materials including biopolymer, acids, enzymes, biochar, and tree resins (Blanck *et al.* 2014, Li *et al.* 2016, Pardo *et al.* 2018, Thomas *et al.* 2019).

The biopolymers have drawn increasing worldwide attention as an example of non-traditional material for soil stabilization, because of their environmentally friendly and sustainable characteristics, and availability at reasonable prices. Various geotechnical characteristics including Atterberg's limits, compressibility, permeability, compaction, shear strength, and shear wave velocity of soils treated with different biopolymer types have been already studied by numerous researchers (Bouazza *et al.* 2009, Chang and Cho 2014, Ayeldeen *et al.* 2016, Chang *et al.* 2016, Latifi *et al.* 2016, Lee *et al.* 2017, Cabalar *et al.* 2017, Cabalar *et al.* 2018, Fatehi *et al.* 2018, Dehghan *et al.* 2019, Kumara and Sujatha 2020, Chang *et al.* 2020). For instance, Chang *et al.* (2016) used Gellan gum type biopolymer to study the geotechnical properties of a sand. The testing results pointed substantial increase in cohesion (c), internal friction angle (φ), and unconfined compression strength (qu) values of the sand with the biopolymer additions. Cabalar *et al.* (2018) carried out an intensive series of laboratory tests including unconfined compressive strength, vane shear, permeability, oedometer, fall-cone, compaction, swelling, and shrinkage tests in different curing times of clay treated with the XG biopolymer at different ratios. The testing results showed that strength of the clay samples increased with both the amount of biopolymer addition and the curing time. They also indicated that permeability of the

*Corresponding author, Professor
E-mail: cabalar@gantep.edu.tr
[a]Research Assistant
E-mail: suleymandemir@kilis.edu.tr



ISSN: 2005-307X (Print), 2092-6219 (Online)

samples with the XG biopolymer was lower, although the compression index and swelling percent values were higher than the samples without any treatment in the clay tested. Furthermore, Kwon *et al.* (2019) have recently studied the geotechnical engineering behavior of a XG treated soft marine soil by considering a series of Atterberg's limits, shear strength at a constant water content, compressive strength in a dry condition, laboratory consolidation, and sedimentation tests. They realized that the XG treatment significantly affects the Atterberg's limits, and shear strength values because of an enhanced interparticle bonding between soil grains induced by a viscous hydrogel formation. They observed that the XG additions delay the consolidation procedure and increase the soil's compressibility. They have further stated that ε- polysine biopolymer provides a great potential for coagulating soil grains in a suspension state as it forms bonding between the soil grains. They eventually identified the XG biopolymer as a soil strengthening material, whilst ε-polylysine biopolymer as a soil-coagulating material.

The fact is that bonding of the soil grains in soil-water-biopolymer mixtures increased shear strength of the mixture with time (Brinker *et al.* 1992, Garcia-Ochoa *et al.* 2000, Grillet *et al.* 2012). Such a time dependent phenomena suggests that short-term behaviors of the soil-water-biopolymer mixtures are more likely to engage in risks resulting in serious problems. Hence, for short-term behavioral analyses in soils, the *su* value appears as one of the most significant design criteria. The laboratory fall cone testing apparatus designed initially in the early 20th century for determining liquid limits of fine-grained soils has been lately utilized for the coarse-grained soils to have advantage of the ease of the testing apparatus on finding the su values (Likos and Jaafar 2014). Despite minor changes in the physical assembly and testing instruments, the fundamentals continue as before (Hansbo 1957, Wroth and Wood 1978, Wood 1985, Leroueil and Le Bihan 1996, Feng 2000, Stone and Kyambadde 2007, Cabalar and Mustafa 2015, O'Kelly 2016, Park *et al.* 2018 Cabalar and Demir 2019). Penetration depth in a specimen is employed to find out the su value by Eq. (1).

$$s_u = k * \frac{mg}{d^2} \tag{1}$$

where $k$=cone angle parameter (0.85), $m$=mass of cone (80 g), and $g$=gravitational acceleration (9.82 m/s$^2$), $d$=fall-cone penetration depth (mm).

The laboratory fall cone has also been accepted as a versatile apparatus for specifying plastic limits, liquid limits, and plastic strength limits of various soil types by many researchers (Feng 2000, Feng 2001, Haigh *et al.* 2013, Cabalar and Mustafa 2015, Zhang *et al.* 2018). Cabalar and Demir (2019) have recently studied the behaviour of unsaturated sand-clay mixtures using a British fall cone testing apparatus. They suggested that penetration depth of the cone mainly depends on water content, size and shape of the sand grains, and the clay content in the mixtures. They have also realized three different responses with penetration depth, which (a) is relatively large for dry mixtures, (b) decreases with increasing water content, and (c) increases with increasing water. Their primary observations have released the significance of transition fines content, and the intergranular void ratio in such mixtures. Likos and Jafar (2014) had conducted fall cone tests on clean sands with different shapes and sizes, and had shown importance of such physical properties on their engineering responses. Actually, there have been numerous studies that show the close relationship between size/shape characteristics of individual soil grains and the overall response of the soil matrix (Terzaghi 1925, Wadell 1932, Olson and Mesri 1970, Lade and Yamamuro 1999, Cavarretta *et al.* 2010, Cabalar *et al.* 2013, Abbireddy and Clayton 2015, Suh *et al.* 2017). However, influences of size and shape characteristics of soil grains on the mechanical responses of the soil matrix still remain one of the most challenging area to be investigated because of the development and evaluation of new instrumentations in laboratory techniques (Gong *et al.* 2019, Zhou *et al.* 2019, Toyota and Takada 2019, Cabalar *et al.* 2021). On the other hand, size and shape characteristics estimates have been fairly well documented and orderly manner (ASTM D6913 2017, Muszynski and Vitton 2012, Abbireddy and Clayton 2015).

In view of the above, this paper presents what is considered to be the first study ever done to see the impact of (i) size/shape features of individual grains, (ii) XG content, and (iii) amount of water in specimens on the su by exploiting fall-cone tests on various shape/size sand-water-biopolymer mixtures to quantify accurately the interaction between each component. Aim of the present study was to find out decent su values of various sands treated with a biopolymer by means of the laboratory fall-cone penetration values. Eventually, the study identifies the results on sands with different sizes and shapes mixed with water and the XG biopolymer at varied contents ranging from 0% to 3% of soil mass. Some correlations have been found between the su values, size/shape of sand grains, amount of biopolymer, and water content. It is believed that correlations developed among the su values, size/shape of individual sand grains, amount of biopolymer, and water content would be very useful for further use by researchers.

## 2. Experimental study

### 2.1 Materials

Crushed Stone Sand (CSS), Narli Sand (NS), the XG, and distilled water were used to prepare the specimens tested in the laboratory fall cone tests. Natural sand samples with rounded shape have been quarried from Narli/Kahramanmaras region, Turkey. The CSS samples with angular shapes were obtained by crushing the massive rocks in the same region. Fig. 1 shows clearly the shapes of CSS an NS grains. Specific gravity (Gs) of both grains were found to be very close to each other (2.65 for NS, and 2.68 for CSS). Two gradations of the CSS and NS samples between 0.15 and 0.30 mm, and 1.00 and 2.00 mm were sieved to maintain uniformity during the tests (Fig. 2). Roundness (R) for the CSS and NS grains was observed as 0.16 and 0.43, while sphericity (S) was found to be 0.55 for CSS and 0.67 for NS grains by means of Muszynski and Vitton (2012).

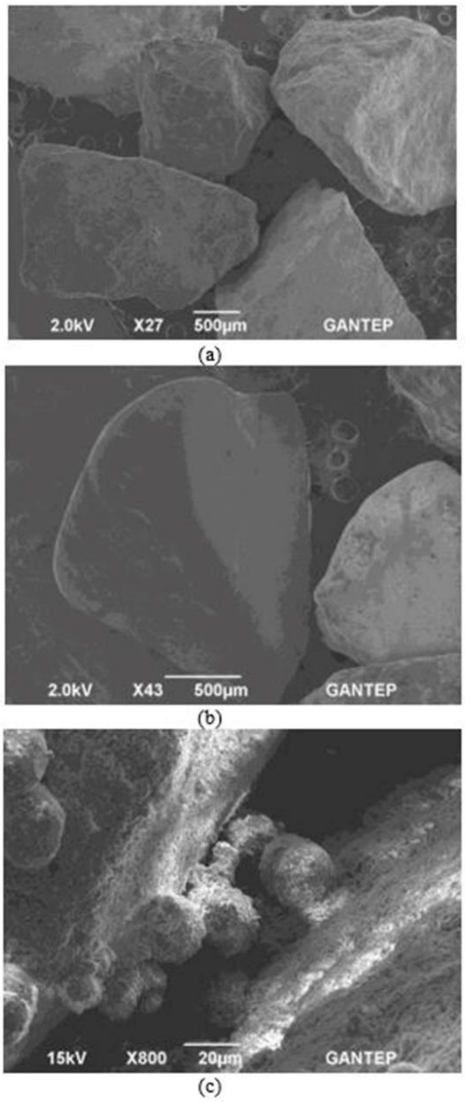


Fig. 1 SEM pictures of the (a) CSS, (b) NS and (c) XG biopolymer covering the grains

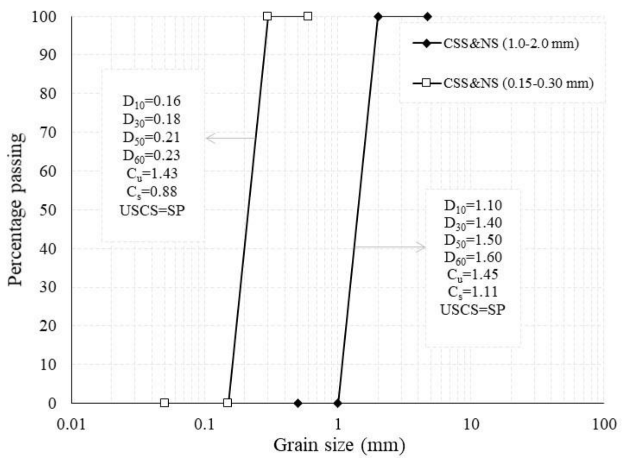


Fig. 2 Grain size distribution of clean sands used during the experimental study

The XG, produced by *Xanthomonas campestris* bacterium, was the biopolymer used in the present investigation (Fig. 1). When the XG is mixed with water, it produces a stable viscous solution with high viscosity pseudo plasticity and high shear stability, which leads its ability to be an engineering binder (Garcia-Ochoa *et al.* 2000, Rosalam and England 2006, Chang *et al.* 2015).

### *2.2 Testing apparatus and specimen preparation*

A British type fall-cone testing machine with a 30˚ cone and with a weight of 80 g was employed in the laboratory works (BS 1377). The machine has a specimen cup with 55 mm diameter, and 40 mm in height. Specimens at various XG contents were arranged by blending dry sand and the XG biopolymer. Then, the specimens were mixed with pre-determined amount of water in a plastic bag in order to allow a complete water diffusion. The prepared specimen was placed into the cup in four layers by means of a spatula. The initial relative density of all specimens was found to be medium dense, with most of them in the region of 39-43%. The amount of penetration was recorded at the end of each 5 seconds. Three to four repetitions were performed in order to provide a reasonable repeatability for the tests. Finally, amount of water in the mixtures was found after completing the testing series (ASTM D2216–19 2019).

## 3. Results and discussions

Testing different soil-water-biopolymer specimens by means of fall-cone apparatus have revealed the effects of size/shape of sand grains, XG content, and the w on penetration of the cone, and accordingly, the su values of the specimens tested. Extensive laboratory testing on the specimens with clean sand grains shows the dependence between d, $s_u$, and size/shape characteristics of the grains (Fig. 3). The NS grains between 1.0 mm and 2.0 mm have the smallest w values changing from about 13% to 21% in order to provide d values covered a range of approximately 15 mm to 25 mm. The $s_u$ values of this sand type fell between 1.2 kPa and 2.9 kPa, with a strength of about 1.8 kPa at 20 mm penetration. The penetration of 20 mm is particularly important because it serves to define water content corresponding the liquid limit (BS1377), and liquefaction susceptibility (Andrews and Martin 2000, Boulanger and Idriss 2006) of a soil matrix, whilst a 2 mm penetration provides the water content at plastic limit (Wasti and Bezirci 1986, Feng 2001, Feng 2004, Sivakumar 2009). The CSS grains between 0.15 mm and 0.30 mm have the w varying from 30% to 37% over a range of about 11 mm to 26 mm penetration depth. The corresponding $s_u$ values were found to be between 1.02 kPa and 5.13 kPa, with a 1.92 kPa at 20 mm penetration. As it can be seen from the plots in Fig. 3 that, regardless of sand type, the $s_u$ values at 20 mm penetration were of course found to be around 1.79 kPa, since same cone was employed for all tests, although the corresponding w values ranged from 19% to 35% (19% for 1.0-2.0 mm NS grains, 24% for the 0.15-0.30 mm NS grains, 28% for the 1.0-2.0 mm CSS grains, and 35% for the 0.15 mm-0.30 mm CSS grains). Samples with angular shape and finer size grains resulted in more water content than those with rounded shape and coarser size grains tested at the 20 mm depth of penetration. It resulted in an overall

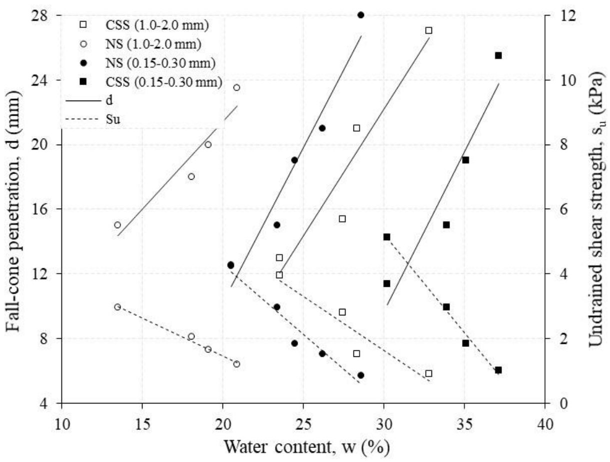


Fig. 3 Fall-cone penetration and the $s_u$ values of clean sands

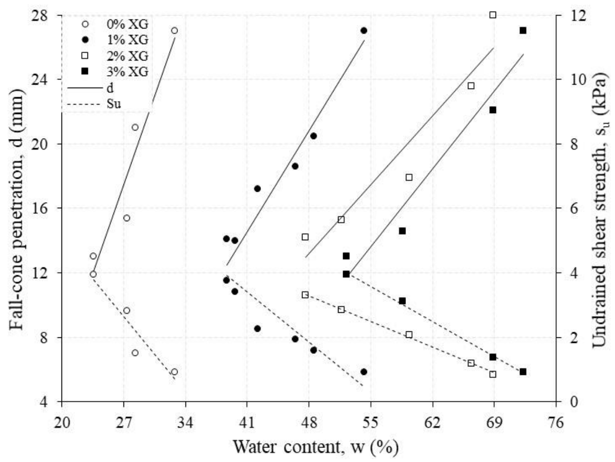


Fig. 6 Fall-cone penetration and the $s_u$ values of 1.0-2.0 mm CSS with various XG contents

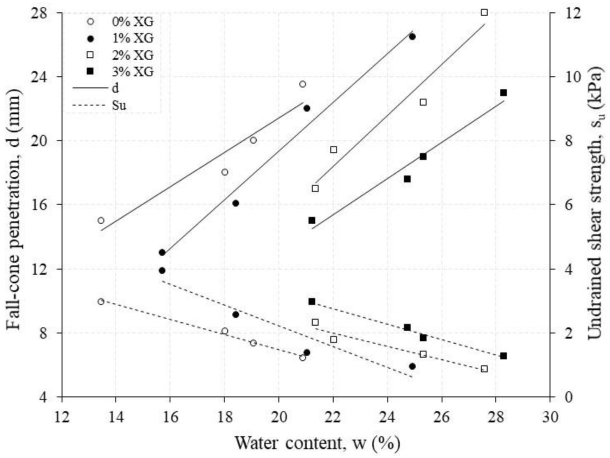


Fig. 4 Fall-cone penetration and the $s_u$ values of 1.0-2.0 mm NS with various XG contents

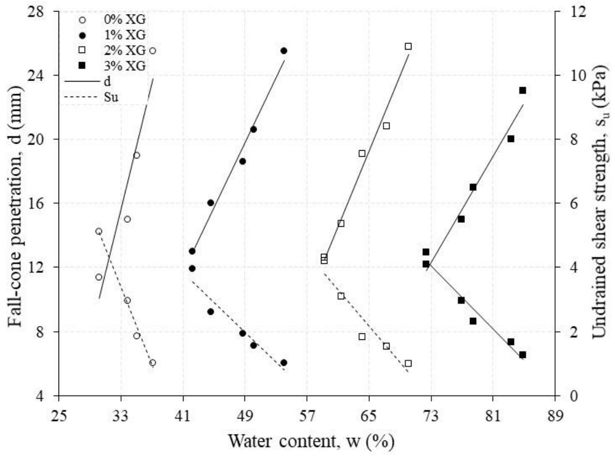


Fig. 7 Fall-cone penetration and the $s_u$ values of 0.15-0.30 mm CSS with various XG contents

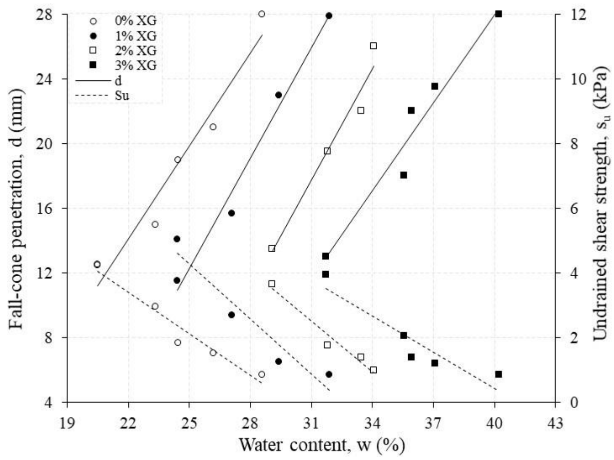


Fig. 5 Fall-cone penetration and the $s_u$ values of 0.15-0.30 mm NS with various XG contents

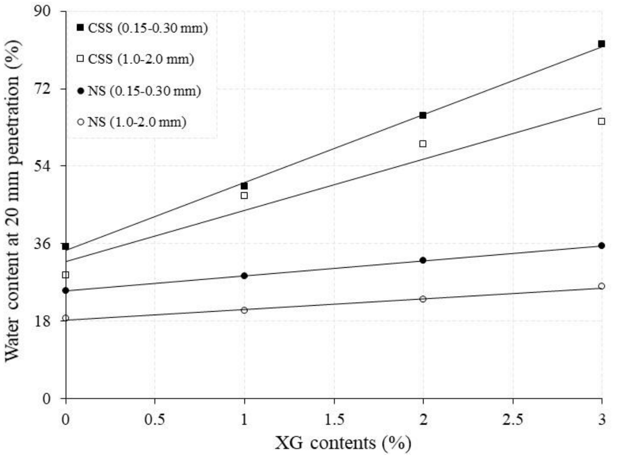


Fig. 8 Water contents at 20 mm fall-cone penetration

increase of w values at 20 mm depth by decreasing size and/or increasing angularity of grains. Increasing finer and angular grains in a soil matrix should be expected contributing to resistance of soil liquefaction. This result demonstrates the importance to focus on size/shape outcomes of the testing results.

The XG, an environmentally friendly biopolymer for improving soils, was used as a binder in the specimens tested during the laboratory works. A basic mixture of specimen has been made using the weight proportions of 1%, 2%, and 3% the XG. The effects of XG on the response of each soil matrix were presented through the Figs. 4-7. A systematic comparison of the testing results revealed

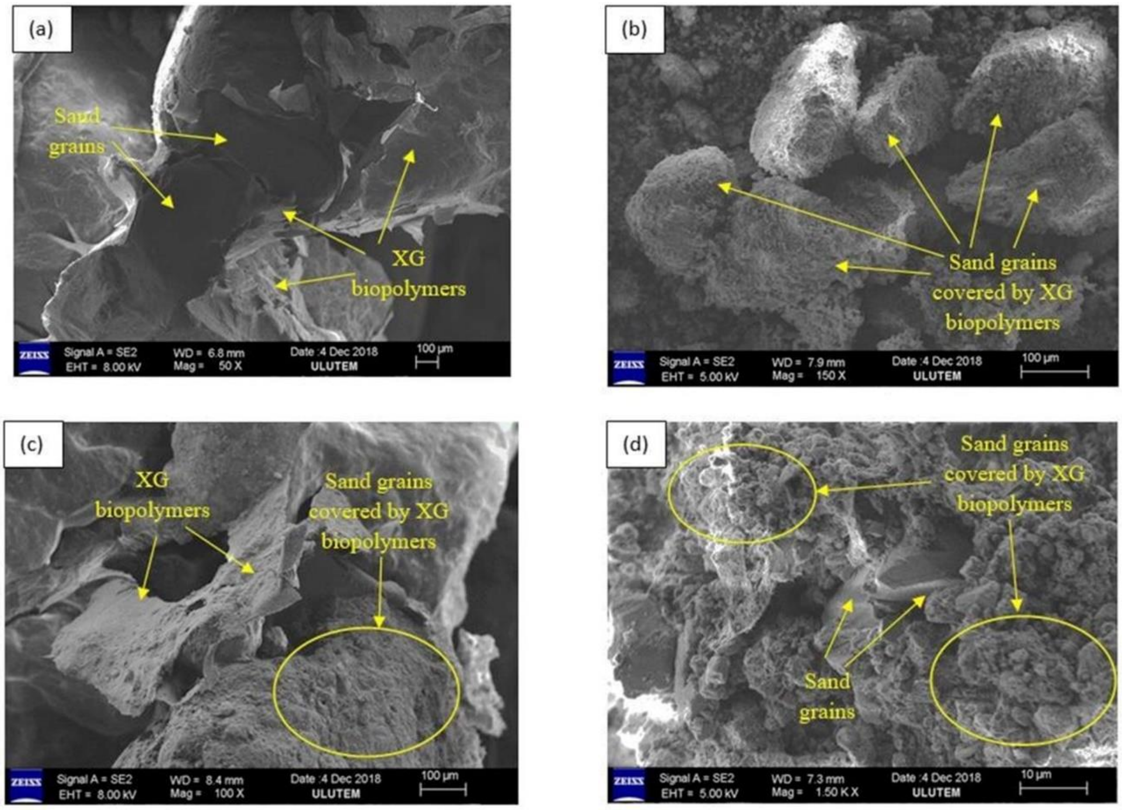


Fig. 9 SEM pictures of the (a) NS (1.0-2.0 mm) with 1% XG (b) CSS (0.15-0.30 mm) with 1% XG (c) NS (1.0-2.0 mm) with 2% XG and (d) CSS (0.15-0.30 mm) with 2% XG

substantial increment in water content of about 10% for a 20 mm cone penetration by mixing 3% XG addition to the NS grains, and an increment in water content of about 35% by mixing 3% XG addition to the CSS grains, regardless of the grain size. This behavior may attribute to a higher water retention of the XG biopolymer than that of the sand used (Chang and Cho 2016, Cabalar *et al.* 2018). Change in XG content in angular sands was observed to be more effective on the testing results than that in rounded sand. Hence, XG addition in to specimens with NS grains should be expected less effective on liquefaction resistance of the samples. As noted from the slopes of best fitting lines in these figures, the samples with finer grain sizes are more susceptible to changes in water content than those with coarse grains. Fig. 8 shows the changes in water contents measured at 20 mm fall-cone penetration for different sands with various XG contents.

The water content corresponding 20 mm penetration showed distinctive differences by grain size and shape. The water contents in the specimens with 0.15-0.30 mm CSS were always found to be well above than the other samples at any XG content. However, the water contents in the specimens with 1.0-2.0 mm NS have always had a place at the bottom for any XG content. Considering around 1.79kPa of $s_u$ values for all the specimens tested, XG addition was found to be more effective on specimens with finer and more angular grains (Fig. 8). It is likely because of water content in the samples with larger voids caused by finer and more angular grains. These findings were found to be well consistent with previous studies in the literature presented by Sridharan and Nagaraj (1999), and Likos and Jaafar (2014). Sridharan and Nagaraj (1999) showed the relation between $s_u$ and water adsorption capacity, while Likos and Jaafar (2014) studied grain size and shape effects on the $s_u$. Furthermore, by following the pioneering study of Seed *et al.* (1983), an attention was drawn by Andrews and Martin (2000) for indicating an analogy between various water contents and shear strength of a soil. A comparative study on the $s_u$ values by using fall cone and triaxial tests reveals an evidence of strong dependency among these testing results. The triaxial testing results obtained by following the procedures described in detail by Cabalar and Clayton (2010), and Cabalar *et al.* (2017) have given out about 25% higher $s_u$ values than the fall cone testing results have. Koumoto and Houlsby (2001), Jonsson and Sellin (2012), O'Kelly (2014), and Farias and Llano-Serna (2016) have reported similar findings in their studies. Fig. 9 presents the scanning electron microscope (SEM) pictures of biopolymer treated sand in order to observe the precipitation of the XG on the sand grains. The pictures indicate solid bonds between the sand grains as well as those coating the surface of each grain. Accordingly, it has been realized that the behaviour of the soil was significantly affected by the biopolymer addition.

## 4. Conclusions

This paper presents an extensive series of laboratory fall-cone tests carried out on specimens composed of different size/shape of sand grains and the XG biopolymer at different quantities. Two different types of sand samples (Crushed Stone Sand, and Narli Sand) with distinct grain shape characteristics (rounded, and angular) and gradations (0.15-0.30 mm, and 1.0-2.0 mm) were used during the experimental studies. Testing results were analyzed to assess both the influence of grain size/shape characteristics and the amount of the XG by varying water contents in the specimens. The results presented in this paper have pointed out three new facets of behaviour:

• The su values of clean sand specimens at specific water contents (w) increase with grain angularity for the sand grains with similar size, and decrease with grain size for grains with similar shape.

• Addition of the XG biopolymer to clean sand increases the su values of specimens at different levels depending on the size and shape of sand grains. The XG biopolymer was found to be more effective on the specimens composed of more fine/angular sand grains than the coarser/rounded grains.

• The XG biopolymer precipitations observed in the SEM pictures verify that the reason of change in soil behaviour was due to the presence of biopolymer in the soil matrix.

• This suggests that it is possible to increase the $s_u$ values of sands by treating the XG biopolymer. However, behaviour of the specimens observed/reported in the present investigation is applicable only to the sands used in the work. Further study is required to evaluate the influences of the XG on soils with different physical and mineralogical characteristic.

## References

Abbireddy, C.O.R. and Clayton, C.R.I. (2015), "The impact of particle form on the packing and shear behaviour of some granular materials: an experimental study", *Granul. Matter*, **17**(4), 427-438. https://doi.org/10.1007/s10035-015-0566-0.

Abu-Farsakh, M., Dhakal, S. and Chen, Q. (2015), "Laboratory characterization of cementitiously treated/stabilized very weak subgrade soil under cyclic loading", *Soils Found.*, **55**(3), 504-516. https://doi.org/10.1016/j.sandf.2015.04.003.

Andrews, D.C.A. and Martin, G.R. (2000), "Criteria for liquefaction of silty soils", *Proceedings of the 12th World Conference on Earthquake Engineering*, Upper Hutt, New Zealand, January-February.

ASTM (2017), D6913/D6913M-17: Standard Test Methods for Particle-Size Distribution (Gradation) of Soils Using Sieve Analysis, ASTM International, West Conshohocken, Pennsylvania, U.S.A.

ASTM (2019), D2216-19: Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass, ASTM International, West Conshohocken, Pennsylvania, U.S.A.

Ayeldeen, M.K., Negm, A.M. and El Sawwaf, M.A. (2016), "Evaluating the physical characteristics of biopolymer/soil mixtures", *Arab. J. Geosci.*, **9**(5), 371. https://doi.org/10.1007/s12517-016-2366-1.

Blanck, G., Cuisinier, O. and Masrouri, F. (2014), "Soil treatment with organic non-traditional additives for the improvement of earthworks", *Acta Geotech.*, **9**(6), 1111-1122. https://doi.org/10.1007/s11440-013- 0251-6.

Bouazza, A., Gates, W.P. and Ranjith, P.G. (2009), "Hydraulic conductivity of biopolymer-treated silty sand", *Géotechnique*, **59**(1), 71-72. https://doi.org/10.1680/geot.2007.00137.

Boulanger, R.W. and Idriss, I.M. (2006), "Liquefaction susceptibility criteria for silts and clays", *J. Geotech. Geoenviron. Eng.*, **132**(11), 1413-1426. https://doi.org/10.1061/(ASCE)1090-0241(2006)132:11(1413).

Brinker, C.J., Hurd, A.J., Schunk, P.R., Frye, G.C. and Ashley, C.S. (1992), "Review of sol-gel thin film formation", *J. Non-Crystal. Solids*, **147**, 424-436. https://doi.org/10.1016/S0022- 3093(05)80653-2.

BSI (1990), BS 1377: Methods of Test for Soils for Civil Engineering Purposes, British Standards Institute, Milton Keynes, U.K.

Cabalar, A.F. and Clayton, C.R.I. (2010). "Some observations of the effects of pore fluids on the triaxial behaviour of a sand", *Granul. Matter*, **12**(1), 87-95. https://doi.org/10.1007/s10035-009-0164-0.

Cabalar, A.F. and Demir, S. (2019), "Fall-cone testing of unsaturated sand-clay mixtures", *P. I. Civil Eng Geotec.*, **172**(5), 432-441. https://doi.org/10.1680/jgeen.18.00155.

Cabalar, A.F. and Mustafa, W.S. (2015), "Fall cone tests on clay-sand mixtures", *Eng. Geol.*, **192**, 154-165. https://doi.org/10.1016/j.enggeo.2015.04.009.

Cabalar, A.F., Awraheem, M.H. and Khalaf, M.M. (2018), "Geotechnical properties of a low-plasticity clay with biopolymer", *J. Mater. Civil Eng.*, **30**(8), 04018170. https://doi.org/10.1061/(ASCE)MT.1943- 5533.0002380.

Cabalar, A.F., Demir, S. and Muklif, M. (2021), "Liquefaction resistance of different size/shape sand-clay mixtures using a pair of bender element mounted mould", *J. Test Eval.*, **49**(1). https://doi.org/10.1520/JTE20180677.

Cabalar, A.F., Dulundu, K. and Tuncay, K. (2013), "Strength of various sands in triaxial and cyclic direct shear tests", *Eng. Geol.*, **156**, 92-102. https://doi.org/10.1016/j.enggeo.2013.01.011.

Cabalar, A.F., Wiszniewski, M. and Skutnik, Z. (2017), "Effects of xanthan gum biopolymer on the permeability, odometer, unconfined compressive and triaxial shear behavior of a sand", *Soil Mech. Found. Eng.*, **54**(5), 356-361. https://doi.org/10.1007/s11204-017-9481-1.

Cavarretta, I., Coop, M. and O'Sullivan, C. (2010), "The influence of particle characteristics on the behaviour of coarse grained soils", *Géotechnique*, **60**(6), 413-423. https://doi.org/10.1680/geot.2010.60.6.413.

Chang, I. and Cho, G.C. (2014), "Geotechnical behavior of a beta-1, 3/1, 6-glucan biopolymer-treated residual soil", *Geomech. Eng.*, **7**(6), 633-647. http://doi.org/10.12989/gae.2014.7.6.633.

Chang, I., Im, J. and Cho, G.C. (2016), "Geotechnical engineering behaviors of gellan gum biopolymer treated sand", *Can. Geotech. J.*, **53**(10), 1658-1670. https://doi.org/10.1139/cgj-2015-0475.

Chang, I., Im, J., Prasidhi, A.K. and Cho, G.C. (2015), "Effects of Xanthan gum biopolymer on soil strengthening", *Constr. Build. Mater.*, **74**, 65-72. https://doi.org/10.1016/j.conbuildmat.2014.10.026.

Chang, I., Lee, M., Tran, A.T.P., Lee, S., Kwon, Y.M., Im, J. and Cho, G.C. (2020), "Review on biopolymer-based soil treatment (BPST) technology in geotechnical engineering practices", *Transp. Geotech.*, 100385. https://doi.org/10.1016/j.trgeo.2020.100385.

Dehghan, H., Tabarsa, A., Latifi, N. and Bagheri, Y. (2019), "Use of xanthan and guar gums in soil strengthening", *Clean Technol. Envir.*, **21**(1), 155-165. https://doi.org/10.1007/s10098-018-1625-0.

Farias, M.M. and Llano-Serna, M.A. (2016), "Simple methodology to obtain critical state parameters of remolded clays under normally consolidated conditions using the fall-cone test", *Geotech. Test. J.*, **39**(5), 1-10, https://doi.org/10.1520/GTJ20150207.

Fatehi, H., Abtahi, S.M., Hashemolhosseini, H. and Hejazi, S.M. (2018), "A novel study on using protein based biopolymers in soil strengthening", *Constr. Build. Mater.*, **167**, 813-821. https://doi.org/10.1016/j.conbuildmat.2018.02.028.

Feng, T.W. (2000), "Fall-cone penetration and water content relationship of clays", *Geotechnique*, **50**(2), 181-187. https://doi.org/10.1680/geot.2000.50.2.181.

Feng, T.W. (2004), "Using a small ring and a fall-cone to determine the plastic limit", *J. Geotech. Geoenviron. Eng.*, **130**(6), 630-635. https://doi.org/10.1061/(ASCE)1090-0241(2004)130:6(630).

Feng, T.W. (2001), "A linear log d log w model for the determination of consistency limits of soils", *Can. Geotech. J.*, **38**(6), 1335-1342. https://doi.org/10.1139/t01-061.

Garcıa-Ochoa, F., Santos, V.E., Casas, J.A. and Gómez, E. (2000), "Xanthan gum: Production, recovery, and properties", *Biotechnol. Adv.*, **18**(7), 549-579. https://doi.org/10.1016/S0734-9750(00)00050-1.

Gong, J., Nie, Z., Zhu, Y., Liang, Z. and Wang, X. (2019), "Exploring the effects of particle shape and content of fines on the shear behavior of sand-fines mixtures via the DEM", *Comput. Geotech.*, **106**, 161-176. https://doi.org/10.1016/j.compgeo.2018.10.021.

Grillet, A.M., Wyatt, N.B. and Gloe, L.M. (2012), "Polymer gel rheology and adhesion", *Rheology*, **3**, 59-80.

Haigh, S.K., Vardanega, P.J. and Bolton, M.D. (2013), "The plastic limit of clays", *Géotechnique*, **63**(6), 435. http://doi.org/10.1680/geot.11.P.123.

Hansbo, S. (1957), "A new approach to the determination of the shear strength of clay by the fall-cone test", *Royal Swedish Geotech. Inst. Proc.*, **14**, 1-49.

Jonsson, M. and Sellin, C. (2012), "Correction of shear strength in cohesive soil: A comparison focused on vane tests in west Sweden", M.Sc. Dissertation, Chalmers University of Technology, Gothenburg, Sweden.

Koumoto, T. and Houlsby, G.T. (2001), "Theory and practice of the fall cone test", *Geotechnique,* **51**(8), 701-712. https://doi.org/10.1680/geot.2001.51.8.701.

Kumara, S.A. and Sujatha, E.R. (2020), "Performance evaluation of β-glucan treated lean clay and efficacy of its choice as a sustainable alternative for ground improvement", *Geomech. Eng.*, **21**(5), 413-422. https://doi.org/10.12989/gae.2020.21.5.413.

Kwon, Y.M., Chang, I., Lee, M. and Cho, G.Y. (2019), "Geotechnical engineering behavior of biopolymer- treated soft marine soil", *Geomech. Eng.*, **17**(5), 453-464. https://doi.org/10.12989/gae.2019.17.5.445.

Lade, P.V. and Yamamuro, J.A. (1997), "Effects of nonplastic fines on static liquefaction of sands", *Can. Geotech. J.*, **34**(6), 918-928. https://doi.org/10.1139/t97-052.

Latifi, N., Horpibulsuk, S., Meehan, C.L., Abd Majid, M.Z., Tahir, M.M. and Mohamad, E.T. (2016), "Improvement of problematic soils with biopolymer—an environmentally friendly soil stabilizer", *J. Mater. Civil Eng.*, **29**(2), 04016204. https://doi.org/10.1061/(ASCE)MT.1943-5533.0001706.

Lee, S., Chang, I., Chung, M.K., Kim, Y. and Kee, J. (2017), "Geotechnical shear behavior of xanthan gum biopolymer treated sand from direct shear testing", *Geomech. Eng.*, **12**(5), 831-847. https://doi.org/10.12989/gae.2017.12.5.831.

Leroueil, S. and Le Bihan, J.P. (1996), "Liquid limits and fall cones", *Can. Geotech. J.*, **33**(5), 793-798. https://doi.org/10.1139/t96-104-324.

Li, M., Chai, S., Du, H. and Wang, C. (2016), "Effect of chlorine salt on the physical and mechanical properties of inshore saline soil treated with lime", *Soils Found.*, **56**(3), 327-335. https://doi.org/10.1016/j.sandf.2016.04.001.

Likos, W.J. and Jaafar, R. (2014), "Laboratory fall cone testing of unsaturated sand", *J. Geotech. Geoenviron. Eng.*, **140**(8), 04014043. https://doi.org/10.1061/(ASCE)GT.1943-5606.0001143.

Mitchell, J.K. (1981), "Soil improvement: State of art report", *Proceedings of the 10th International Conference on Soil Mechanics and Foundation Engineering*, Stockholm, Sweden, June.

Mitchell, J.K. and Santamarina, J.C. (2005), "Biological considerations in geotechnical engineering", *J. Geotech. Geoenviron. Eng.*, **131**(10), 1222-1233. https://doi.org/10.1061/(ASCE)1090-0241(2005)131:10(1222).

Muszynski, M.R. and Vitton, S.J. (2012), "Particle shape estimates of uniform sands: Visual and automated methods comparison", *J. Mater. Civil Eng.*, **24**(2), 194-206. https://doi.org/10.1061/(ASCE)MT.1943- 5533.0000351.

O'Kelly, B.C. (2014), "Characterisation and undrained strength of amorphous clay", *P. I. Civil Eng Geotec.*, **167**(3), 311-320. http://doi.org/10.1680/geng.11.00025.

O'Kelly, B.C. (2018), "Fall-cone strength testing of municipal sludges and residues", *Environ. Geotech.*, **5**(1), 18-30. https://doi.org/10.1680/jenge.15.00080.

Olson, R.E. and Mesri, G. (1970), "Mechanisms controlling compressibility of clays", *J. Soil Mech. Found. Div.*, **96**(SM6), 1863-1878.

Pan, Y.Z., Rossabi, J., Pan, C.G. and Xie, X.Y. (2019), "Stabilization/solidification characteristics of organic clay contaminated by lead when using cement", *J. Hazard. Mater.*, **362**, 132-139. https://doi.org/10.1016/j.jhazmat.2018.09.010.

Pardo, G.S., Orense, R.P. and Sarmah, A.K. (2018), "Cyclic strength of sand mixed with biochar: Some preliminary results", *Soils Found.*, **58**(1), 241-247. https://doi.org/10.1016/j.sandf.2017.11.004.

Park, T.W., Kim, H.J., Tanvir, M.T., Lee, J.B. and Moon, S.G. (2018), "Influence of coarse particles on the physical properties and quick undrained shear strength of fine-grained soils", *Geomech. Eng.*, **14**(1), 99-105. https://doi.org/10.12989/gae.2018.14.1.099.

Rafalko, S.D., Filz, G.M., Brandon, T.L. and Mitchell, J.K. (2007), "Rapid chemical stabilization of soft clay soils", *Transp. Res. Rec.*, **2026**(1), 39-46. https://doi.org/10.3141/2026-05.

Rosalam, S. and England, R. (2006), "Review of xanthan gum production from unmodified starches by Xanthomonas comprestris sp", *Enzyme Microb. Technol.*, **39**(2), 197-207. https://doi.org/10.1016/j.enzmictec.2005.10.019.

Saadeldin, R. and Siddiqua, S. (2013), "Geotechnical characterization of clay-cement mix", *B. Eng. Geol. Environ.*, **72**(3), 601-608. https://doi.org/10.1007/s10064-013-0531-2.

Schaefer, V.R., Mitchell, J.K., Berg, R.R., Filz G.M. and Douglas S.C. (2012), "Ground improvement in the 21st century: a comprehensive web-based information system", *Proceedings of the GeoCongress 2012*, Oakland, California, U.S.A., March.

Seed, H.B., Idriss, I.M. and Arango, I. (1983), "Evaluation of liquefaction potential using field performance data", *J. Geotech. Eng.*, **109**(3), 458-482. https://doi.org/10.1061/(ASCE)0733-9410(1983)109:3(458).

Shrestha, R. and Al-Tabbaa, A. (2012), "Development of predictive models for cement stabilized soils", *Proceedings of the 4th International Conference on Grouting and Deep Mixing*, New Orleans, Louisiana, U.S.A., February.

Sivakumar, V., Glynn, D., Cairns, P. and Black, J.A. (2009), "A new method of measuring plastic limit of fine materials", *Géotechnique*, **59**(10), 813-823.

https://doi.org/10.1680/geot.2009.59.10.813.
Sridharan, A. and Nagaraj, H.B. (1999), “Absorption water content and liquid limit of soils”, *Geotech. Test. J.*, **22**(2), 127-133. https://doi.org/10.1520/GTJ11271J.
Stone, K. and Kyambadde, B.S. (2007), “Determination of strength and index properties of fine-grained soils using a soil minipenetrometer”, *J. Geotech. Geoenviron. Eng.*, **133**(6), 667-673. https://doi.org/10.1061/(ASCE)1090-0241(2007)133:6(667).
Suh, H.S., Kim, K.Y., Lee, J. and Yun, T.S. (2017), “Quantification of bulk form and angularity of particle with correlation of shear strength and packing density in sands”, *Eng. Geol.*, **220**, 256-265. https://doi.org/10.1016/j.enggeo.2017.02.015.
Terashi, M. and Juran, I. (2000), “Ground improvement—state of the art”, *Proceedings of the International Conference on Geotechnical and Geological Engineering*, Melbourne, Australia, November.
Terzaghi, K. (1925), *Erdbaumechanik auf Bodenphysikalischer Grundlage*, Deuticke, Leipzig, Vienna, Austria.
Thomas, A., Tripathia, R.K. and Yadu, L.K. (2019), “Alkali-activated GGBS and enzyme on the swelling properties of sulfate bearing soil”, *Geomech. Eng.*, **19**(1), 21-28. https://doi.org/10.12989/gae.2019.19.1.021.
Toyota, H. and Takada, S. (2019), “Effects of gravel content on liquefaction resistance and its assessment considering deformation characteristics in gravel-mixed sand”, *Can. Geotech. J.*, **56**(12), 1743-1755. https://doi.org/10.1139/cgj-2018-0575.
Wadell, H. (1932), “Volume, shape, and roundness of rock particles”, *J. Geol.*, **40**(5), 443-451. https://doi.org/10.1086/623964.
Wasti, Y. and Bezirci, M.H. (1986), “Determination of the consistency limits of soils by the fall cone test”, *Can. Geotech. J.*, **23**(2), 241-246. https://doi.org/10.1139/t86-033.
Wood, D.M. (1985), “Some fall cone tests”, *Geotechnique*, **35**(1), 64-68. https://doi.org/10.1680/geot.1985.35.1.64.
Wroth, C.P. and Wood, D.M. (1978), “The correlation of index properties with some basic engineering properties of soils”, *Can. Geotech. J.*, **15**(2), 137-145. https://doi.org/10.1139/t78-014.
Zhang, T., Cai, G. and Liu, S. (2018), “Reclaimed lignin-stabilized silty soil: undrained shear strength, atterberg limits, and microstructure characteristics”, *J. Mater. Civil Eng.*, **30**(11), 04018277. https://doi.org/10.1061/(ASCE)MT.1943-5533.0002492.
Zhou, W.H., Jing, X.Y., Yin, Z.Y. and Geng, X. (2019), “Effects of particle sphericity and initial fabric on the shearing behavior of soil-rough structural interface”, *Acta Geotech.*, **14**(6), 1699-1716. https://doi.org/10.1007/s11440-19-00781-2.

*IC*