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Strength and durability characteristics of biopolymer-treated desert sand

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Abstract. Biopolymer treatment of geomaterials to develop sustainable geotechnical systems is an important step towards the reduction of global warming. The cutting edge technology of biopolymer treatment is not only environment friendly but also has widespread application. This paper presents the strength and slake durability characteristics of biopolymer-treated sand sampled from Al-Sharqia Desert in Oman. The specimens were prepared by mixing sand at various proportions by weight of xanthan gum biopolymer. To make a comparison with conventional methods of ground improvement, cement treated sand specimens were also prepared. To demonstrate the effects of wetting and drying, standard slake durability tests were also conducted on the specimens. According to the results of strength tests, xanthan gum treatment increased the unconfined strength of sand, similar to the strengthening effect of mixing cement in sand. The slake durability test results indicated that the resistance of biopolymer-treated sand to disintegration upon interaction with water is stronger than that of cement treated sand. The percentage of xanthan gum to treat sand is proposed as 2-3% for optimal performance in terms of strength and durability. SEM analysis of biopolymer-treated sand specimens also confirms that the sand particles are linked through the biopolymer, which has increased shear resistance and durability. Results of this study imply xanthan gum biopolymer treatment as an eco-friendly technique to improve the mechanical properties of desert sand. However, the strengthening effect due to the biopolymer treatment of sand can be weakened upon interaction with water.

Keywords: desert sand; bio-soil improvement; Xanthan gum; biopolymer; strength; durability

1. Introduction

Anthropogenic global warming not only induces environmental issues such as sea level rise and abnormal climate change, but also gives rise to geotechnical and geoenvironmental issues such as land degradation (erosion) and desertification. In modern civil infrastructure practices, all new or rehabilitation practices require ground improvement, regardless of the scale of construction. Over the past century, various ground improvement methods have been developed and are widely employed in geotechnical engineering implementations.

Generally, various ground improvement approaches can be classified into mechanical or

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chemical methods. Mechanical methods improve the soil by densification (compaction) or dewatering (drainage, consolidation), while most chemical methods enhance inter-particle attachment through cementation by mixing or injecting ordinary Portland cement or chemical additives (Chang *et al*. 2016b). Shooshpasha and Shirvani (2015) enhanced the mechanical properties of a sandy soil by utilizing cementing agents. Chang *et al*. (2016c) studied the improvements of permeability, compressibility, static and liquefaction strengths of in-situ soils by grouting. The basic principles of both mechanical and chemical ground improvement techniques were unchanged in the recent past. However, common chemical materials used in soil improvement have environmental concerns such as high emission of greenhouse gases during their production and soil eco-system disturbance after its application into ground. In detail, ordinary cement production emits carbon dioxide, a significant greenhouse gas, during chemical calcination and fuel burning. It has been reported that 5% of the global carbon dioxide emissions are induced by the cement industries (Worrell *et al*. 2001). Both the disuse and the recycling of cement-concrete waste are potentially hazardous to the environment due to the potential for pollutant leakage into the soil and groundwater.

Meanwhile, several alternatives such as geopolymers, alkali activated cement, geo-cement, and inorganic polymer concrete have been developed in attempts to reduce or replace cement use. However, the carbon dioxide reduction efficiency of these methods is insufficient due to their dependency on ordinary cement and heavy industry by-products (e.g., blast furnace slag, fly ash, etc.) (Chang *et al*. 2015b).

Rapidly increasing demand for environmentally-friendly and sustainable development have motivated geotechnical engineers to find and develop unconventional engineered ground improvement methods (DeJong *et al*. 2006, Mitchell and Santamarina 2005). Therefore, demand for the development of environmentally-friendly construction materials that are relatively harmless and can be easily reused without environmental impacts is increasing significantly in the 21st century (Cabalar and Canakci 2011).

In conventional geotechnical engineering, a largely unrecognized fact is that soil is an organic medium with inhabitation of thousands of microbes and bacteria (DeJong *et al*. 2006). However, recent bio-soil attempts such as bio-mediated or bio-inspired approaches show that biological treatment of soils could meet the same engineering requirements with less environmental concerns (Chang *et al*. 2016b).

Moreover, biological soil treatment is not only appropriate for ground improvement but also holds promise for greenhouse gas reduction strategies (Vink *et al*. 2003). Biocementation shows potential to replace the energy intensive mechanical compaction process or expensive and environmentally harmful chemical grouting (Ivanov and Chu 2008). The future prospects of biological soil treatments have been demonstrated in other fields such as in the petroleum industry to direct the oil flow in the required direction, in concrete technology to remediate cracks (Ramachandran *et al*. 2001), and in the development of shields for zonal remediation and stabilization of contaminated soils (Khachatoorian *et al*. 2003). Research in biology and earth science has enabled important advances in understanding the crucial involvement of microorganisms in the evolution of the earth, the ubiquitous presence of microorganisms in near surface soils and rocks, and participation in mediating and facilitating important geochemical characteristics of soil (Mitchell and Santamarina 2005).

Biopolymers are polymers produced by living organisms, and most biopolymer applications are in the field of medical engineering, such as drug delivery systems, wound healing, and surgical implantations (Van de Velde and Kiekens 2002). Biopolymers are sustainable and environ

Table 1 Recent attempts on soil improvement with biopolymer treatments

Soil type	Biopolymer	The effects of bio improvement	Remarks
Sand	Agar gum	Efficiency in undisturbed sampling	Sutterer *et al*. 1996
Silty sand	Xanthan gum	Reduction in hydraulic conductivity	Khachatoorian *et al*. 2003
Silty sand	Xanthan gum, guar gum and sodium alginate	Reduction in permeability	Bouazza *et al*. 2009
Clay	Xanthan gum and guar gum	Increase in undrained shear strength and liquid limit	Nugent *et al*. 2009
Sand	Xanthan gum	Improvement in shear strength	Cabalar and Canakci 2011
Sand, yellow soil	Beta-glucan	Improvement in uniaxial compressive strength of soils	Chang and Cho 2012, 2014
Sand	Agar and modified starch	Increase in unconfined compressive strength, cohesion and stiffness	Khatami and O'Kelly 2012
Sand	Xanthan gum	Shear strength	Qureshi *et al*. 2014
Sand	Xanthan gum	Slake durability	Qureshi *et al*. 2015
Sand to clay	Xanthan gum	Soil strengthening due to Xanthan gum treatment	Chang *et al*. 2015a
Sand to clay	Agar gum and Gellan gum	Soil strengthening through thermo-gelation of thermo-gelating biopolymers	Chang *et al*. 2015c
Residual soil	Beta-glucan Xanthan gum	Soil erosion reduction and vegetation improvement via biopolymer treatment	Chang *et al*. 2015d
Sand	Gellan gum	Gellan gum biopolymer-treatment effect on geotechnical engineering behavior of sand	Chang *et al*. 2016a
Sand, silt	Xanthan gum, modified starch, guar gum	Increase in shear resistance and reduction in permeability	Ayeldeen *et al*. 2016

mentally-friendly materials because they are generally produced from anthropogenic agricultural non-food crops. To achieve the aim of environmentally-friendly development, in the fields of soil science, geotechnical engineering, and geo-environmental engineering, biopolymers have been employed as soil stabilizers to enhance the mechanical response of ground against the external loading and the environment (Table 1).

Among various types of biopolymers, xanthan gum has been commonly used in recent studies due to its appropriate strengthening efficiency and economic feasibility based on massive commercialization (Chang *et al*. 2015b). Xanthan gum is a polysaccharide that is made by the *Xanthomonas campestris* bacterium, and is generally used as a viscosity thickener due to its hydrocolloid rheology (Barrére *et al*. 1986). Xanthan gum has been introduced to geotechnical engineering to reduce the hydraulic conductivity of silty sand via pore filling (Bouazza *et al*. 2009, Khachatoorian *et al*. 2003) as well as to increase the undrained shear strength of soil by increasing the liquid limit (Nugent *et al*. 2009). Another recent study studied possibilities of using xanthan gum as a soil strengthener, and showed that xanthan gum preferentially forms firm xanthan gum-clayey soil matrices via hydrogen bonding (Chang *et al*. 2015a). Khatami and O'Kelly

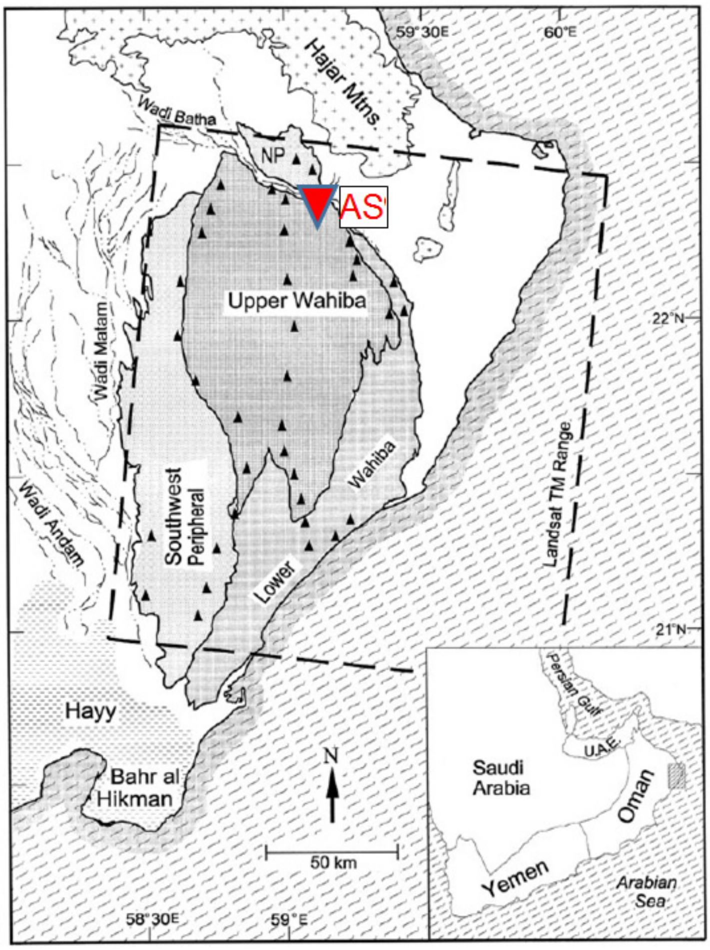


Fig. 1 Location of Al-Sharqia sand dunes, Oman (Pease *et al*. 1999)

(2013) reported the mechanical behavior of sand treated with agar and modified starch. Their results showed an increase in unconfined compressive strength, cohesion, and stiffness of the treated sand. Qureshi *et al*. (2015) investigated the effects of wetting and drying on xanthan gum treated sand and concluded that the xanthan gum treated sand has good durability against slaking. A remarkable increase in shear resistance and a reduction in the permeability of sand and silt were reported by Ayeldeen *et al*. (2016). They employed xanthan gum, modified starch, and guar gum to improve sand and silt. Agar gum has been attempted for soil temporary supports and advanced undisturbed sampling (Sutterer *et al*. 1996). Chang *et al*. (2016a) reported an increase in shear strength parameters and reduction in permeability of sand treated with gellan gum. Further, they interpreted that the gellan gum treated sand is sensitive to moisture but durable enough for application to support shallow foundations.

Therefore, biopolymer treatment, especially xanthan gum, is a promising soil improvement method for enhancing soil strength and erosion resistance. Moreover, it has been suggested that biopolymers could be applied for anti-desertification practices such as surface erosion reduction and afforestation programs to combat desertification (Chang *et al*. 2015d). In this study, real desert sand from Oman is treated by xanthan gum biopolymer to evaluate the geotechnical engineering behavior when xanthan gum biopolymer is implemented in real in situ deserts to combat desertification practices.

2. Materials

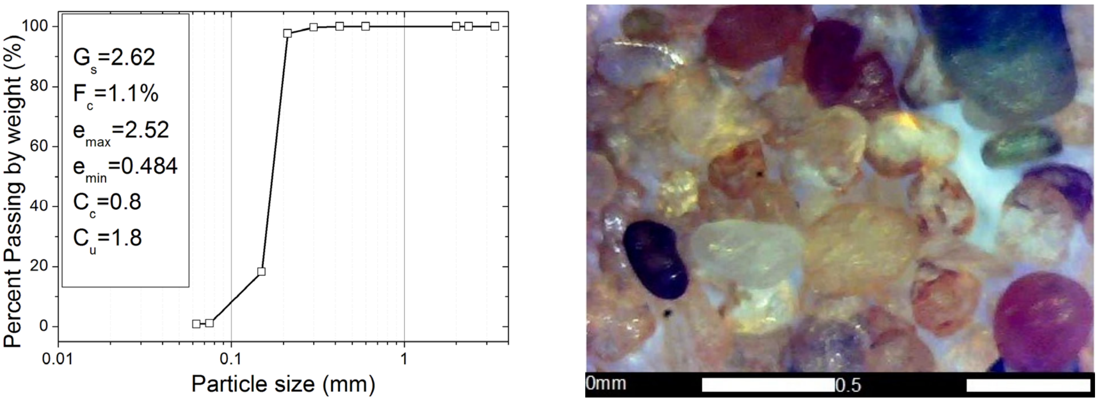
2.1 Site of interest: *Al-Sharqia Desert Sand*

Sand is sampled from Al-Bidiya in the northern part of Wahiba sand dunes (Fig. 1), in Al-Sharqia Region, which is about 200km to the south of Capital Muscat. The Wahiba Sand formed in the Quaternary period (Glennie *et al*. 2002) is composed of two physiographic units that can be roughly divided into northern and southern regions. The Northern Wahiba is predominantly a large megaridge system, whereas the Southern Wahiba mostly comprises linear dunes, sand sheets, and sabkha fields (Pease and Tchakerian 2002). Carbonate sands are present throughout the Wahiba sand area with some quartz-rich sands in the Southern region.

The Al-Sharqia sand (AS) used in this study is sampled from the Northern region. The grain size distribution (British Standards 1990a) of the sand is shown in Fig. 2(a). The sand can be classified as poorly-graded fine sand (SP) according to the Unified Soil Classification System (USCS). The sand has a specific gravity (British Standards 1990a) of G_s = 2.62 and a fine content of 1.1%. The standard proctor compaction test (British Standards 1990b) gave a maximum dry density (γ_d) of 1.64 g/cm^3 at an optimum water content of 19.5%. The microscope image of AS indicates the ellipse-type particle shape with smooth surfaces and lack of fines (Fig. 2(b)), which are typical particulate characteristics of quartz sand weathered and transported via aeolian processes in deserts (Khalaf and Gharib 1985).

2.2 Xanthan Gum (*XG*)

Xanthan gum ($C_{35}H_{49}O_{29}$), which has high viscous rheology and was discovered in the 1950s, is a natural anionic polysaccharide composed of D-glucuronic acid, D-mannose, pyruvylated mannose, 6-O-acetyl D-mannose, and a 1,4-linked glucan (Garcia-Ochoa *et al*. 2000, Hassler and



(a) Gradation analysis (b) Photomicrograph

Fig. 2 Physical properties of Al-Sharqia Sand (AS)

Doherty 1990), which is the most rigid biological repeating molecule (Yevlampieva *et al*. 1999). The most well-known characteristics of Xanthan gum are pseudo plasticity (viscosity degradation with an increase of shear rate) (Milas and Rinaudo 1986) and high shear stability (Chen and Sheppard 1980) even at low concentrations. Moreover, it has several desirable properties including, pH stability, storage stability, and ionic salt compatibility (Hassler and Doherty 1990). Because of these properties, XG has found a wide range of applications in cosmetics, oil, paper, paint, pharmaceuticals, and food and textile industries as a gelling, thickening, or suspending agent, and as a flocculent or for viscosity control

3. Experimental program

3.1 Xanthan Gum-treated Al-Sharqia Sand Specimens (*ASG*)

Sampled Al-Sharqia sand (AS) from the site was oven dried at 105°C for 24 hours. Purified XG powder (Sigma-Aldrich, CAS number 11138-66-2) was used in this study. Distilled-deaired water was used to dissolve XG powder with different concentrations to avoid the effects of any additional factors such as the chemical components that may exist in portable water (Chen *et al*. 2013). XG powder was gently added into the water to avoid clumping, and then the solution was mixed until a homogeneous solution was obtained. Xanthan gum solution concentrations (XG content to the mass of water) were set as 1, 2, 3, and 5%, according to the final target xanthan gum ratio (%) to the dry mass of sand.

After a uniform xanthan gum solution was prepared, sand was thoroughly mixed with the XG solution to obtain homogeneous XG-sand mixtures. The initial water content for mixing was set between 12 to 15%, according to the optimal water content obtained from compaction tests. Xanthan gum-sand mixtures were molded into a cylindrical shape with 50 mm diameter and 100 mm height to be used for unconfined compression and triaxial tests (Fig. 3). However, it was difficult to obtain uniform initial dry densities of xanthan gum-treated sand specimens due to rheology variation of xanthan gum gels with higher XG content. Therefore, all specimens (Fig. 3) were prepared at the respective maximum dry density obtained from compaction tests.

All xanthan gum-treated AS sand specimens were cured in an oven at 45°C for 28 days. The temperature for curing was selected so as to reproduce the desert temperature. For comparison,

Fig. 3 Specimens for Unconfined compression and triaxial tests

Table 2 Summary of the specimens for compression tests

Sr. No.	Specimen ID	Xanthan gum (%)	Cement (%)	Dry density (g/cc)
1	AS	0	-	1.640
2	ASG1	1	-	1.670
3	ASG2	2	-	1.640
4	ASG3	3	-	1.635
5	ASG5	5	-	1.630
6	ASC10	-	10	1.580

conventionaly engineered – i.e., 10% cement-treated – specimens were prepared simultaneously (Lorenzo and Bergado 2004, Walker 1995). Cement-treated AS sand samples were prepared with 10% cement content to the mass of sand with a 0.5 water-cement ratio. Uniformly mixed cement-AS sand mixtures were molded into a cylindrical shape (50 mm in diameter and 100 mm in height) and cured at the same condition (45°C) as XG-treated AS sand samples were cured. A summary of the characteristics of the prepared specimens is provided in Table 2.

3.2 Testing program

3.2.1 Basic geotechnical engineering properties

A standard proctor compaction test was performed for determining the maximum dry density for each mix type and its corresponding optimal moisture content. The consistency limits (*LL*, *PL*, and *PI*) of the xanthan gum treated specimens were obtained in accordance with international standards. Unconfined compression tests were performed with an axial strain rate as 1%/min. Three specimens were measured and averaged to represent the mechanical behavior of each single condition of sand treatment. All the tests were performed in accordance with British Standards 1990c.

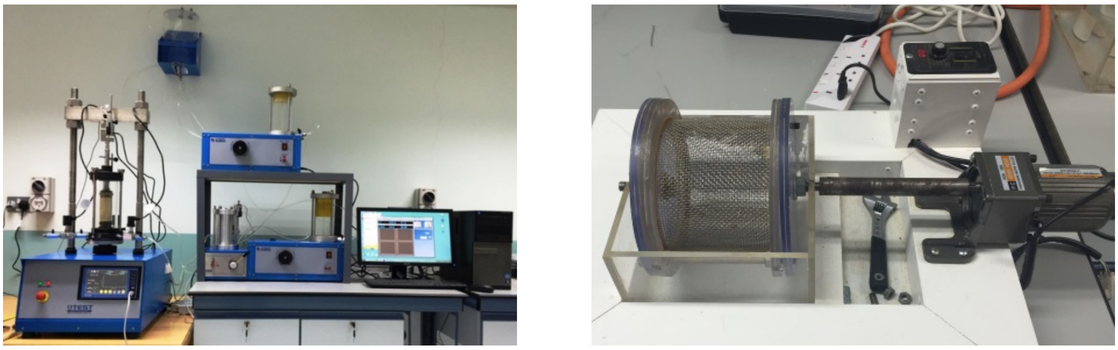
3.2.2 Triaxial test

To study the mechanical behavior of ASG specimens in a confined state, unconsolidated undrained (*UU*) triaxial tests were performed in accordance with BS 1377-7 (British Standard Institute 1990c). State-of-the-art triaxial test equipment (Utest, Turkey) was employed, as shown in Fig. 4(a). The salient features of the equipment are a 50kN load-cell, a LVDT of 50 mm stroke length, maximum confining pressure of 2MPa, axial strain controlled loading, and an eight channel data logging system.

Unconsolidated undrained (UU) responses of untreated and XG-treated Al-Sharqia sand were evaluated by performing a series of triaxial tests on dried untreated sand (AS) and xanthan gum-treated sand (ASG) with 1, 2, 3, and 5% xanthan gum content. The strain rate was kept at 1%/min. The tests were performed at three different radial stresses (σ_r) i.e., 50, 100, and 150 kPa to delineate the shear strength parameters. All the tested specimens had moisture content less than 3%, and it should be noted that the xanthan gum gel was already dehydrated before testing.

3.2.3 Slake durability test

The effects of wetting and drying on the durability of ASG are elucidated by performing standard slake durability tests (Franklin and Chandra 1972). The slake durability test device used in this study is shown in Fig. 4(b).



(a) A-state of-the-art triaxial test equipment (b) Slake durability test device

Fig. 4 Laboratory testing system

One of the main concerns in the biotreatment of soil is the water effects on the strengthening behavior. The authors therefore performed slake durability tests on xanthan gum treated and cement treated sand specimens. The tests were performed as per standard procedures (Franklin and Chandra 1972) The slake durability index after each slaking cycle is reported as the percentage of initial dried weight to the dried weight at the end of each slaking cycle. The specimens were tested up to four slaking cycles and the slake durability indices after each cycle were obtained, i.e., SD1, SD2, SD3, and SD4.

Scanning Electron Microscope (SEM) images

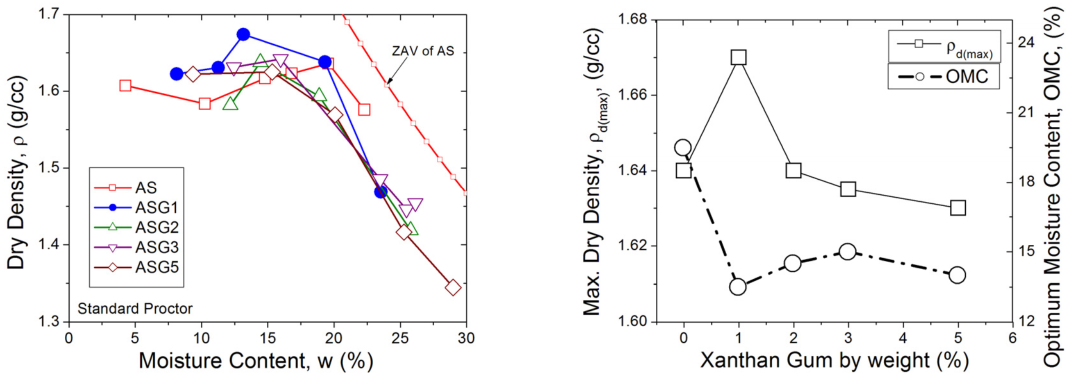
The change in the mechanical and durability behavior of sand treated with biopolymer is further assessed through a scanning electron microscope (SEM) analysis. A field emission scanning electron microscope (JSM-7600F) was used to capture microscale images of both xanthan gum-treated and untreated sands.

4. Results and analysis

4.1 Maximum dry density and optimal moisture content of XG-treated Al-Sharqia Sand

Structural composition of soil is generally represented by the dry density and the void ratio, which are important parameters governing the strength of geomaterials. Results of standard proctor tests performed on Al-Sharqia sand (AS) and xanthan gum-treated Al-Sharqia sand (ASG) are summarized in Fig. 5(a).

The maximum dry density (γ_d) immediately increases with XG 1% treatment, while it decreases and becomes slightly lower than untreated sand at higher (≥ 2%) xanthan gum content (Fig. 5(b)). In detail, the maximum γ_d of Al-Sharqia sand increases from 1.64 g/cm^3 (untreated) to 1.67 g/cm^3 with 1% xanthan gum treatment (ASG1). The increase in the maximum γ_d of sand due to 1% xanthan gum treatment implies enhanced particle compressibility due to the lubricant effect of xanthan gum gels in inter-granular pores. However, the maximum γ_d decrease for higher xanthan gum content appears to be altered by the increased stiffness with higher biopolymer gel concentrations (xanthan gum to water ratio in mass), which results in structural swelling and accompanying γ_d decrease (Chang and Cho 2014).



(a) Plot of dry density and moisture content

(b) Max. dry density and moisture content plotted against xanthan gum content

Fig. 5 Compaction characteristics of xanthan gum treated Al-Sharqia sand

Meanwhile, optimal moisture content variation of xanthan gum-treated sands is symmetric to the γ_d variation (Fig. 5(b)), which shows the lowest value at the 1% xanthan gum-treated condition (ASG1). The initial increase of the maximum γ_d at low xanthan gum content is accordant with the viscosity increase and lubricant effect of gum-water solutions (Ayeldeen *et al*. 2016, Chang and Cho 2014). However, after a certain turning point, higher biopolymer gel viscosity induces significant swelling pressure which results in separation of sand particles with no further increase in the maximum γ_d (Ayeldeen *et al*. 2016).

4.2 LL, PL, and PI of Xanthan gum-treated Al-Sharqia Sand

In general, consistency limits (*PL* and *LL*) of untreated cohesionless desert sands are difficult to evaluate. However, the results shown in Fig. 6 demonstrate enhanced soil plasticity due to viscous pore fluid rheology induced by xanthan gum treatment.

The *LL* of 1%, 2%, 3%, and 5% xanthan gum-treated sand was evaluated as 18.9%, 23.6%, 28.0%, and 35.3%, respectively. The *LL* gradually increases with greater xanthan gum content, indicating the effect of hydrophilic property of xanthan gum on the plasticity behavior of sand.

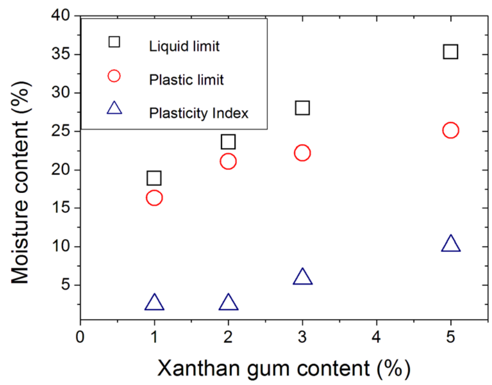


Fig. 6 Change in consistency limits of xanthan gum treated Al-Sharqia sand at different gum contents

The presence of xanthan gum and water in soil forms xanthan gum hydrogels around and between sand particles due to the hydrophilic water adsorption and the swelling rheology of XG, which provides plasticity to cohesionless sands. Thus, as the concentration of XG in the soil mass increases, the water retention capacity of the soil should increase simultaneously. As a result, the non-plastic nature of cohesionless Al-Sharqia sand becomes plastic and cohesive with xanthan gum treatment.

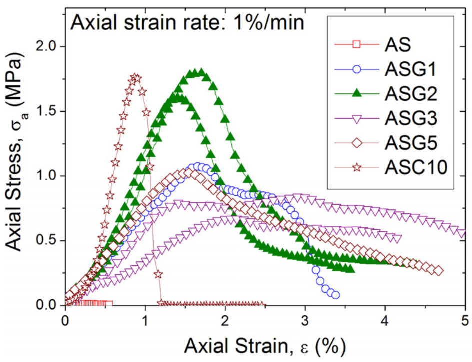
Simultaneously, an increase in *PL* is observed with increased xanthan gum content, the overall plasticity ($PI = LL - PI$) is enhanced with xanthan gum biopolymer treatment. The higher LL and PI of soil generally imply higher undrained shear strength and lower hydraulic conductivity (Sharma and Bora 2003). Therefore, xanthan gum treatment is expected to significantly enhance the shear strength and the erosion resistance of cohesionless desert sands, thereby performing an important role in soil degradation control and combat desertification in arid and semi-arid regions (Chang *et al*. 2015d).

4.3 Unconfined compressive strength of Xanthan gum-treated Al-Sharqia Sand

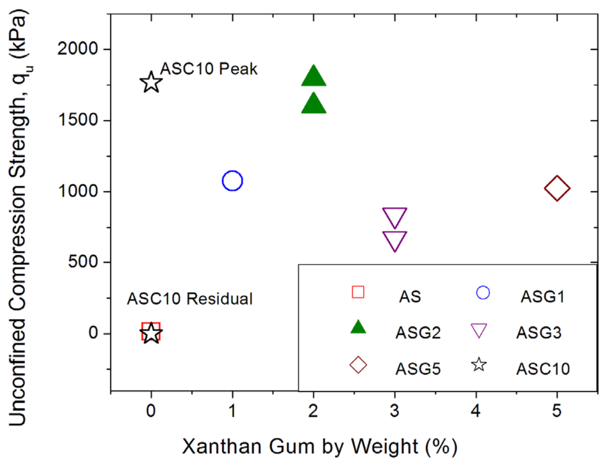
Unconfined compression tests were performed on dried xanthan gum-treated Al-Sharqia sand specimens. Typical plots of axial stress-strain curves are displayed in Fig. 7(a). The unconfined compression response of the 10% cement-treated AS sand specimen is also plotted in Fig. 7(a). The average unconfined compressive strengths (UCS) of all tested specimens are plotted against xanthan gum content variation in Fig. 7(b).

The average UCS of untreated AS sand is 15 kPa, while xanthan gum treatment induces significant UCS values of 1076 kPa, 1700 kPa, 753 kPa, and 1024 kPa with 1%, 2%, 3%, and 5% xanthan gum content, respectively. 10% cement treatment also renders a UCS as high as 1,767 kPa. The peak UCS of 2% xanthan-treated sand (1,700 kPa in average) is comparable to that of 10% cement treatment (1,767 kPa in average), which is in line with the strengthening efficiency provided by Chang *et al*. (2015a).

However, 10% cement-treated sand shows brittle behavior with almost zero residual strength after failure, while xanthan gum-treated sands show higher ductility and significant residual (post-

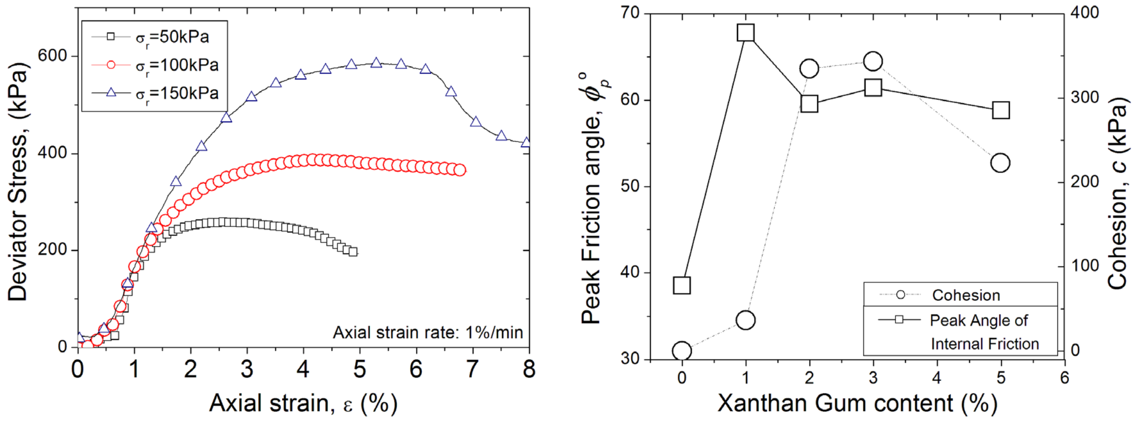


(a) Stress strain plot



(b) UCS plotted against xanthan gum content

Fig. 7 Unconfined compressive strength of xanthan gum-treated Al-Sharqia sand



(a) A typical plot of deviator stress and axial strain of Al-Sharqia Sand

(b) Shear strength parameters plotted against xanthan gum content

Fig. 8 Triaxial test results of xanthan gum treated sand specimen in dry state

0 cycle ASG1 | 0 cycle ASG2 | 0 cycle ASG3 | 0 cycle ASG5 | 0 cycle ASC10

1 cycle ASG1 | 1 cycle ASG2 | 1 cycle ASG3 | 1 cycle ASG5 | 1 cycle ASC10

2 cycles ASG1 | 2 cycles ASG2 | 2 cycles ASG3 | 2 cycles ASG5 | 2 cycles ASC10

3 cycles ASG1 | 3 cycles ASG2 | 3 cycles ASG3 | 3 cycles ASG5 | 3 cycles ASC10

4 cycles ASG1 | 4 cycles ASG2 | 4 cycles ASG3 | 4 cycles ASG5 | 4 cycles ASC10

Fig. 9 Changes in xanthan gum treated (ASG) and cement treated (ASC) specimens due to slaking cycles peak) strengthening behavior. In the case of the residual response, the specimens treated with a small percentage of xanthan gum took precedence over specimens treated with a higher percent of cement. The results reported by Chang *et al*. (2016c) from unconfined compression tests on dry specimens of gellan gum treated sand revealed similar behavior. Thus, the inter-particle strengthening resulted from the formation of a thick and high-tensile dehydrated gel of xanthan gum among the sand particles, which continues to support the inter-particle bonding between sand particles after failure.

4.4 Triaxial tests result of Xanthan gum-treated Al-Sharqia sand

Typical deviatoric stress–strain responses of untreated Al-Sharqia sand (γ_d = 1.64 g/cm^3) are shown in Fig. 8(a).

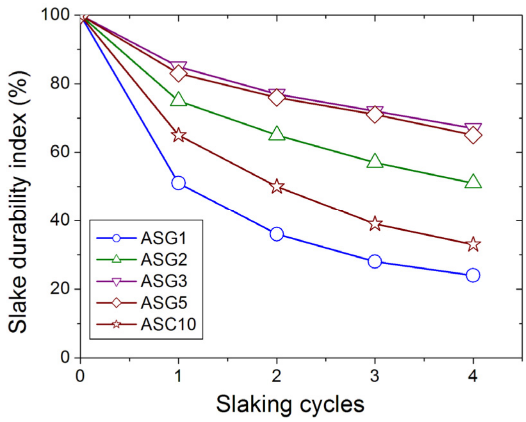
Inter-particle cohesion of xanthan gum-treated AS sand becomes 0, 36 kPa, 334 kPa, 343 kPa, and 223 kPa, for 0 (untreated), 1%, 2%, 3%, and 5% xanthan gum content, respectively (Fig. 8(b)). A remarkable increase of *c* is observed for xanthan gum content higher than 2%, while cohesion enhancement appears to diminish after 3% xanthan gum content.

Meanwhile, ϕ of untreated AS sand was 38°, while that of dried xanthan gum-treated AS sand reaches remarkably high values between 58° and 67°, as shown in Fig. 8(b). The highest value of ϕ is observed in sand treated with 1% xanthan gum content. The ϕ decrease and convergence after 2% xanthan gum content is consistent with the γ_d behavior of xanthan gum treated AS sand shown in Fig. 5(b). Thus, it can be concluded that 2% and higher xanthan gum content for AS sand treatment renders looser particle composition due to the existence of thick XG gels inside inter-granular pores. Meanwhile, *c* increases significantly after 1% xanthan gum content, which indicates rheological viscosity of xanthan gum gels to dominant the *c* values of xanthan gum-treated sands. However, the decrease of *c* at 5% xanthan gum content should be verified with additional mechanical and biochemical approaches in future studies.

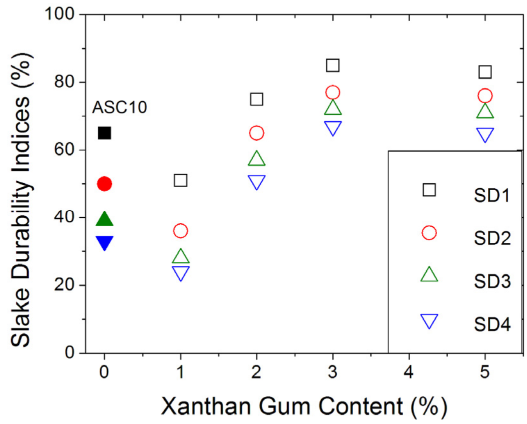
4.5 Slake durability

The qualitative changes in the specimen at the end of each slaking cycle are presented in Fig. 9. For XG-treated sand, the specimen with the lowest xanthan gum content (ASG1) shows the lowest durability, where the overall durability performance in the slake durability test appears to increase with higher xanthan gum content. Meanwhile, an interesting observation is that the 10% cement-treated specimen (ASC10) also shows a weak durability, which is slightly higher than that of 1% xanthan gum-treated sand (ASG1), but lower than that of 2, 3, and 5% xanthan gum-treated conditions. In general, cement-treatment in geotechnical engineering practices is preferred due to the expected high strength and durability of cement-treated soils. However, in the case of AS desert sand, xanthan gum treatment is more appropriate in terms of both strengthening and durability.

A decrease in the slake durability index is observed after each slaking cycle for all the specimens, as shown in Fig. 10(a). The slake durability indices obtained after 1, 2, 3, and 4 slaking cycles (SD1, SD2, SD3, and SD4) are plotted against the xanthan gum content in Fig. 10(b). The slake durability indices of ASC10 are also plotted in this figure. It can be seen that that durability of treated sand against slaking increases with an increase in xanthan gum content up to 3%. A higher content of xanthan gum hydrogel keeps the sand particles amalgamated during the wetting cycle, but the cement-treated specimens show significant strength degradation with wetting and

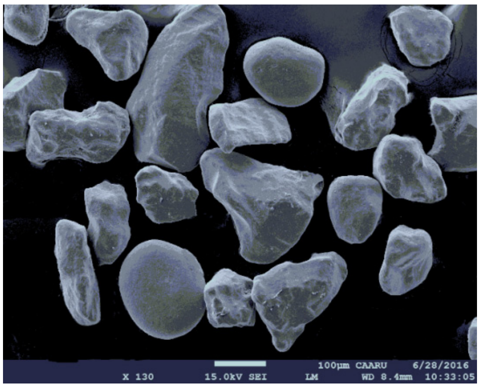


(a) Plot of slake durability and slaking cycles

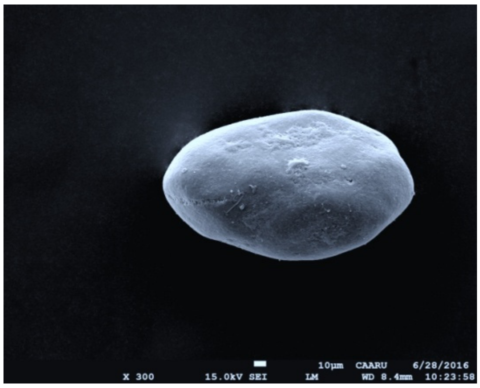


(b) Slake durability indices plotted against xanthan gum content

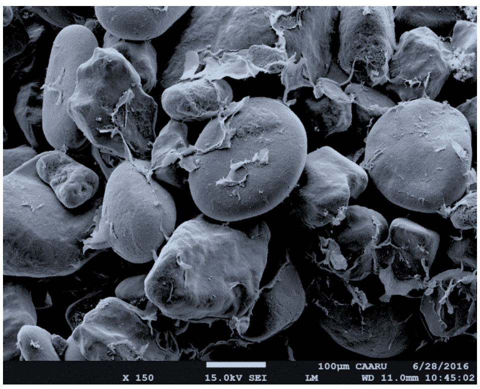
Fig. 10 Slake durability test results of xanthan gum (ASG) and cement treated (ASC) Al-Sharqia sand



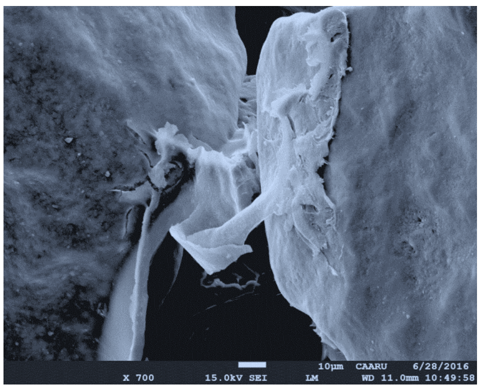
(a) Natural Al-Sharqia sand



(b) Smooth surface of Al-Sharqia sand



(c) Biopolymer-treated sand with 2% xanthan gum content



(d) Inter-particle bonding with xanthan gum films (2% xanthan gum-treated sand).

Fig. 11 SEM images of xanthan gum-treated and untreated Al-Sharqia sand drying cycles. During the drying cycle, the XG gel is dehydrated but remains available for the next wetting cycle.

4.6 Microscopic structure of Xanthan Gum-treated Al-Sharqia Sand

The improvement in durability and the shearing resistance have been further investigated qualitatively at a microscale. Photomicrographs of virgin Al-Sharqia sand are presented in Figs. 11(a) and (b). A typical structure of desert sand is evident, having subrounded particles that experienced wind erosion. The observed asperities on the particle surfaces provide potential locations for the attachment of biopolymer gel. The photomicrographs of XG-treated sand at a concentration of 2% xanthan gum shown in Figs. 12(c) and (d) reveal the biopolymer accumulated between the spaces of particles. The strength and durability of the biopolymer-treated sand depends on the strength of the biopolymer links between the particles. These links also improve the biopolymer-treated sand to withstand higher strains, which is confirmed with the post-failure residual strength observed during the unconfined compression tests. During the process of slaking these biopolymer links are hydrated and keep the soil intact even at the saturated state, thereby reinforcing the biopolymer-treated sand and enhancing its durability.

5. Conclusions

The objective of the current research was to investigate the possibility of improving the engineering properties of dune sands by treatment with xanthan gum. Based on the results presented in this paper, the following conclusions can be drawn.

The xanthan gum substantially increases the unconfined compressive strength of the treated sand. The unconfined compressive strength increases with xanthan gum content up to 2% and thereafter decreases with an increase in xanthan gum content. The unconfined compressive strength of sand treated with a cement content of 10% was on the same order as that of 1% treatment with xanthan gum.

The results of unconsolidated undrained triaxial tests show enhanced shear properties (inter-particle friction angle and cohesion) of sand induced by xanthan gum biopolymer treatment. The dehydrated xanthan gum gel acted as a cementing agent between the sand particles. The angle of internal friction of biopolymer-treated sand increases with the xanthan gum content up to 1% and then decreases, but remains higher than that of untreated sand. The cohesion of biopolymer-treated sand also increases with xanthan gum content up to 2% and then decreases, but remains higher than that of untreated sand. Thus, the treatment with xanthan gum effectively improved the strength characteristics of Al-Sharqia sand. To achieve optimal results in terms of biopolymer induced strengthening of sand, a mix percentage of 2-3% is optimal.

The standard proctor tests delineated that the maximum dry density of 1% xanthan gum treatment to sand was the highest. Thus, it is recommended that in-situ compaction for biopolymer-treated sand layers to be performed with 1% xanthan gum content, which is expected to render the densest structural composition with high bearing capacity.

The response of biopolymer-treated sand to slaking also increases with the content of xanthan gum. The slake durability index of biopolymer-treated sand increases up to 3% gum content and remains unchanged thereafter. In comparison, the cement treatment showed low durability against slaking. The results of this study indicate that xanthan gum biopolymer treatment of sand can be a sustainable and eco-friendly practice in the desert environment that will not adversely affect the biodiversity and will be very attractive to develop geotechnical systems.

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