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Improvement of the geotechnical engineering properties of dune sand using a plant-based biopolymer named serish

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Abstract. Recently, the construction industry has focused on eco-friendly materials instead of traditional materials due to their harmful effects on the environment. To this end, biopolymers are among proper choices to improve the geotechnical behavior of problematic soils. In the current study, serish biopolymer is introduced as a new binder for the purpose of sand improvement. Serish is a natural polysaccharide extracted from the roots of Eremurus plant, which mainly contains inulins. The effect of serish biopolymer on sand treatment has been investigated through performing unconfined compressive strength (UCS), California bearing ratio (CBR), as well as wind erosion tests. The results demonstrated that serish increased the compressive strength of dune sand in both terms of UCS and CBR. Also, wind erosion resistance of the sand was considerably improved as a result of treatment with serish biopolymer. A microstructural study was also conducted via SEM images; it can be seen that serish coated the sand particles and formed a strong network.

Keywords: biopolymer; sand; SEM; soil improvement; sustainable materials; unconfined compressive strength

1. Introduction

Cohesionless dune sand shows low shear strength in an unconfined state (e.g., ϕ= 36.66º and c=0.17 kPa (Fatehi *et al.* 2018)). In addition, non-plastic soil such as dune sand possesses major problems including low geotechnical strength and high settlement potential (AlKarni and ElKholy 2012). Approximately one-third of the Earth's land surface comprises deserts, and 20% of deserts' topography is covered by dune sand (Desert Features 2019). Therefore, building activities and the growth of economy in these areas necessitate carrying out geotechnical investigations for improving characteristics of the dune sand.

Soil treatment and ground improvement have been essential practices since the rise of civilization. Employing natural adhesives and materials such as lime, bitumen and mud were the initial methods of soil enhancement (Chang *et al.* 2016). Predominantly, chemical soil improvement aims to enhance the mechanical properties of problematic soils by using soil additives. Chemical soil treatment is a method of improving soil characteristics by adding external materials and enhancing chemical bonding among soil particles. Various types of materials have been used as binders regarding this matter, among which cement and lime are the most common additives because of their low price and abundant supply (Kumar *et al.* 2007, Jahandari *et al.* 2020). Despite having good efficiency in increasing the soil strength and erosion resistance, cement and lime have several detrimental impacts on the environment (Chang *et al.* 2016).

For instance, cement and lime result in comparatively high carbon footprint, groundwater contaminations and introduce foreign materials into the ecosystem (Joga and Varaprasad 2019). Lime (CaO) is also the main ingredient in most common types of cement, which is manufactured through the high-temperature calcination of crushed limestone ($CaCO_3$). The released CO_2 accounts for more than 5% of global anthropogenic CO_2 emissions up to 2019 (Lim *et al.* 2019; Gregory *et al.* 2021). Global warming is a disastrous consequence of increasing greenhouse gases emissions; 2015 to 2020 was the warmest period experienced since 1880 (Chang *et al.* 2019, 2020 in Review 2021, Kazemi *et al.* 2022). In addition, sanding, grinding, or cutting concrete can release enormous amounts of dust containing high levels of crystalline silica (Jahandari *et al.* 2021). Prolonged or repeated exposure can lead to a disabling and often fatal lung disease called silicosis (Cement Hazards 2001). Meanwhile, alternative ground improvement materials including geopolymers (Davidovits 2008), geocement (Krivenko and Kovalchuk 2007), and inorganic polymer concrete (Sofi *et al.* 2007) have attempted to reduce the use of cement in civil engineering, while the CO_2 reduction effectiveness of those materials is

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(a) Eremurus plant (b) Eremurus roots (c) Serish powder

Fig. 1 Production of serish powder

still insufficient due to their origin from massive fossil fuel consuming industries (Chang and Cho 2012, Miraki *et al.* 2021). Hence, an expanding research area has been developed for environmentally friendly ground improvement.

The investigations of soil binders with biological origins are mainly being driven by the demand for more sustainable and eco-friendly soil improvement methods (Chang *et al.* 2018, Ghadir *et al.* 2021, Sadeghian *et al.* 2021). Biological materials possess many environmental and workable advantages, such as low greenhouse gas emission (Mohanty *et al.* 2002), soil erosion reduction (Chang *et al.* 2015, Kwon *et al.* 2020, Kwon *et al.* 2021) and effective soil strengthening when used for soil improvement (Lee *et al.* 2017, Lee *et al.* 2019). Biopolymers are polymers produced by biological systems such as microorganisms, plants and animals, or synthesized chemically (Van de Velde and Kiekens 2002; Bahmani *et al.* 2017). With the purpose of environmentally friendly and sustainable development, different biopolymers have already been employed for ground improvement (Ayeldeen *et al.* 2017, Hataf *et al.* 2018, Shariatmadari *et al.* 2020, Soldo *et al.* 2020).

Currently, xanthan gum has been actively used to enhance the mechanical properties of various types of soils including sand, silt and clay (Chen *et al.* 2019, Dehghan *et al.* 2019, Joga and Varaprasad 2019, Kwon *et al.* 2019, Singh and Das 2019, Seo *et al.* 2021). Also, other biopolymers have been investigated as soil additives and found to be practical with enhancing effects on the soil. For example, casein, gellan gum, agar gum, guar gum and alginate have improved different characteristics of soils such as compressive strength, shear strength, and many other properties (Chang *et al.* 2016, Smitha and Sachan 2016, Fatehi *et al.* 2018, Chang and Cho 2019, Fatehi *et al.* 2019). Moreover, one of the crucial environmental problems for loose soils, mainly occurring in arid regions, is wind erosion resulting in desertification (44% of global desertification is related to wind erosion) (Jiang *et al.* 2019). Fugitive dust produced by wind erosion covers roads and crops causing a reduction in agriculture productivity (Alsanad 2011). Results have shown that both xanthan gum and guar gum coat mine tailings (MT) particles generating a strong cross-linking network, therefore, enhancing the surface strength, increasing the moisture retention capacity and significantly reducing dust beyond that of only using water wetting (Chen *et al.* 2015).

Studies demonstrate that biopolymers could be taken into consideration as an environment-friendly alternative for providing complex conditions such as microbial injection method for soil improvement (Fatehi *et al.* 2018). Also, the search for various biopolymers with different characteristics and effects on soils continues, which can be utilized either locally or globally. In this paper, a plant originated biopolymer, serish, is introduced as a new soil binder to enhance the geotechnical engineering properties of poorly-graded arid region sand. The production process of this biopolymer and its main characteristics are also illustrated.

The mechanical and geotechnical engineering behaviors of serish-treated sand are studied through a set of laboratory tests, including unconfined compressive strength test (UCS), California bearing ratio (CBR) test, and wind erosion test. Scanning electron microscopy (SEM) observation is also conducted to clarify the microscopic interaction between serish and sand grains.

2. Materials and methods

2.1 Serish

Serish (or Syrysh) is a natural and plant-based adhesive obtained from the roots of the *Eremurus* plant. Eremurus is a perennial plant of the *Liliaceae* family, which the genus has nearly 50 species and mainly grows in western and central Asia (Li *et al.* 2000, Dashti *et al.* 2005). Various species of Eremurus are cultivated as ornamental plants to grow flowers in several countries. *Eremurus persicus* and *Eremurus spectabilis M. B.* are species that grow in arid and rocky hills (Kamenetsky and Rabinowitch 1999, Vala *et al.* 2011). The leaves are traditionally exploited for relieving constipation and treatment for diabetes, liver and stomach disorders as well as rheumatism and physical weaknesses (Vala *et al.* 2011). Polysaccharides have been reported as chemical constituents of species in the genus Eremurus (Li *et al.* 2000). The roots of these perennial monocots have traditionally been utilized to cure jaundice, pimples and bone fractures (Pourfarzad *et al.* 2014, Pourfarzad *et al.* 2015, Kohkesh *et al.* 2019, Koohkesh *et al.* 2020).

Serish powder is generally extracted from the roots by drying and grinding the roots into powder as shown in Fig. 1. A viscous and adhesive solution will be formed by

Table 1 Basic soil properties of the dune sand used in this study

D_{50} (mm)	C_u	C_c	G_s	USCS	e_{max}	e_{min}	OMC (%)	Maximum Dry Density (g/cm³)
0.27	1.87	0.88	2.65	SP	0.94	0.55	16	1.69

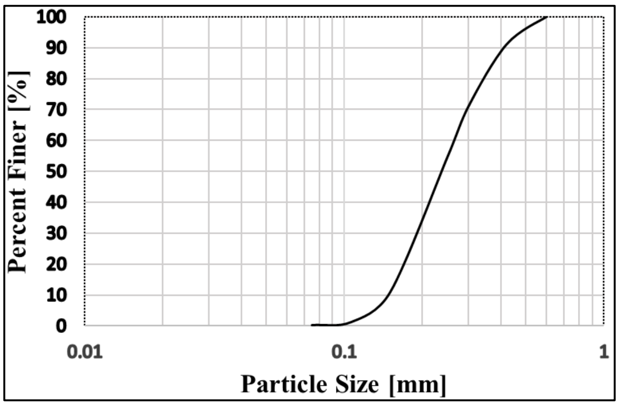


Fig. 2 Particle size distribution curve of the soil used in the study

mixing serish powder and water. Serish solution is commonly used in various industries such as carpentry, shoemaking, bookbinding, box building (Eghtedarnejad and Mansouri 2016). The mean particle size of serish powder is approximately 0.05 mm, where it consists of 60 percent Inulin, 20 percent Laevulose, and 20 percent water, ash, and minerals (Khorasani *et al.* 2006). Inulins are a group of naturally occurring polysaccharides, and Laevulose or D-fructose (or fruit sugar), is a simple ketonic monosaccharide found in many plants. In this paper, serish is attempted to improve the geotechnical behavior of the arid dune sand.

2.2 Soil

The dune sand used in this study is a uniformly graded fine dune sand sampled from the Lut desert of Iran (32° 7’ 2.91” N; 55° 5’ 54.1824” E). The particle size distribution and basic soil properties are presented in Fig. 2 and Table 1, respectively. According to Table 1, the maximum dry density and optimum moisture contents were 16% and 1.69 g/cm^3, respectively, obtained using the standard Proctor compaction method (ASTM 2005).

2.3 Experimental program

2.3.1 Sample preparation

To decide the adequate amount of water and additive based on the optimum moisture content and dry density of soil, the dune sand was air-dried (with room temperature of 20-23 ºC and humidity of about 40%). To prepare serish-sand mixtures, dry serish powder, with the contents of 0.5, 1, 1.5, 2 and 3% (serish content to the mass of the soil), was manually (i.e., hand) mixed with sand. The distilled water was then added to the mixture and blended thoroughly (Fig. 3(a)). Water was added to the dry soil–binder mixtures based on optimum moisture content and mixed to ensure a homogeneous mixture. In details, as the optimum moisture content of dune sand is 16% (Table 1) the mass ratios between sand : water : serish was set as 100 : 16 : 1, to obtain a 1% (serish to sand ratio in mass) serish-treated sand condition.

2.3.2 Unconfined compression test

For UCS assessment, cylinder samples (38 mm in diameter and 80 mm in height) were prepared by compacting serish-treated soil into a polypropylene cylinder mold. To ensure appropriate sample extraction from the mold, a smooth linear groove was cut along the side of the polypropylene molds, where two pipe hangers were used to maintain the grooved mold tight and intact during specimen preparation (Fig. 3(b)).

Uniaxial compressive tests were conducted to investigate the serish content (i.e., 0.5, 1, 1.5, 2, and 3%) and drying time (1, 3, 7, 14, and 28 days) effects on the UCS and elastic modulus of serish-treated dune sand (Fig. 4). A standard universal testing machine (WFEng-Ltd-5Ton-CM apparatus) was used with a strain rate of 1% per minute (0.8 mm/min) in accordance with ASTM D2166 (ASTM 1991), where three samples were tested to obtain a reliable average value for each condition.

In the current study, the UCS samples’ length-to-diameter (aspect) ratio (2.1:1) was slightly higher than the typical aspect ratio (2:1). Although the standard aspect ratio of 2:1 offers a zone of near-uniform strain/stress within the 1/3~1/2 of the specimen length so that the shear failure is more plausible for unconfined or triaxial compression tests (Jardine *et al.* 1984; O'Kelly and Naughton 2008), the higher aspect ratio (2.1:1) adopted in this study could provide a longer central zone of uniform strain/stress which is known to have less impact on the measurement of the material’s shear resistance.

2.3.3 California Bearing Ratio (CBR) test

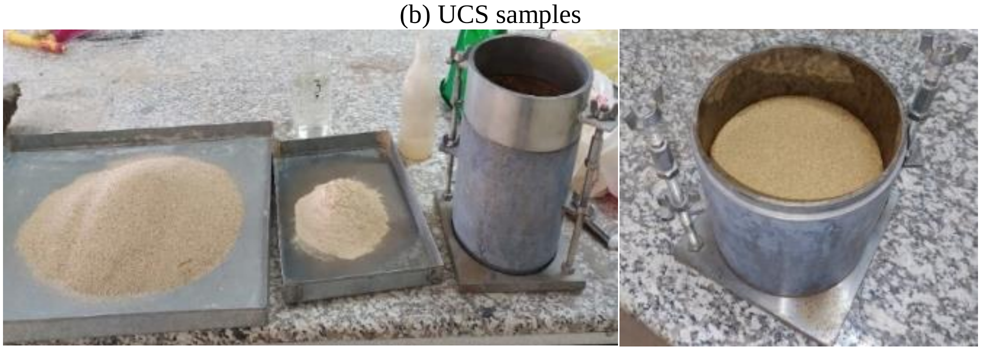
For CBR test, a cylinder rigid metal mold with an inner diameter of 152 mm and height of 1780 mm was used (Fig. 3(c)). The soil was compacted in three layers at optimum moisture content. Also, serish and water contents were added based on the maximum soil dry density and optimum moisture content. CBR tests were conducted by following ASTM D1883-16 at the penetration depth of 5 mm (ASTM 1883) (Fig. 5). The 1% and 2% serish-treated dune sand, and clean dune sand were dried for 7 days at room temperature (20-23ºC) before conducting unsoaked CBR tests. Treated and untreated samples were prepared and compacted at the maximum dry density and optimum moisture content levels.

2.3.4 Wind erosion test

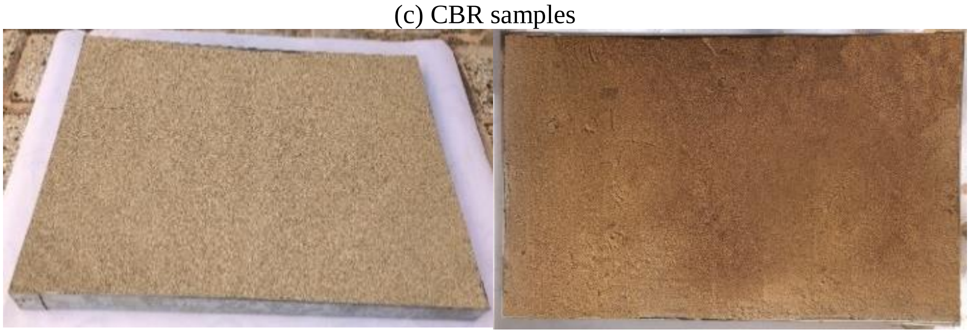
The nature of the surface over which the wind is traveling can significantly influence the wind velocity profile and the wind energy near the surface. A soil surface

(a) Example of specimen mixing

(b) UCS samples



(c) CBR samples



(d) Erosion test samples

Fig. 3 Specimen preparation

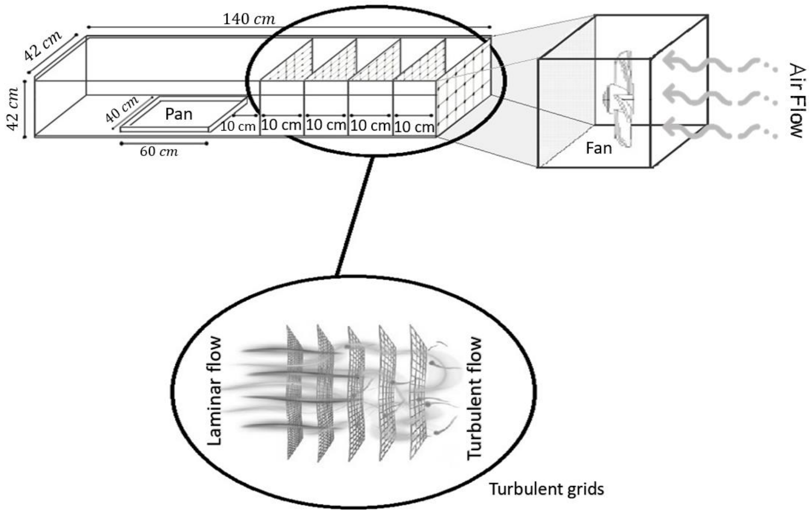
Fig. 4 Unconfined compression test

that is rough or protected with non-erodible material will demand a stronger wind to initiate particle movement compared to a bare smooth surface. Soil particles are moved by the wind in three ways: surface creep (particles roll along the surface), saltation (particles hop over the surface), and suspension (particles move above the surface in the turbulent flow). Pure sand moves easily by surface creep and saltation, causing problems such as damaging young plants, health complications, and loss and deposition within localized areas (Wagner 2013). Soil additives such as serish are one of the potential solutions to stabilizing dune sand surfaces and preventing erosion.

Water and serish were employed to stabilize dune sand against wind erosion. Serish contents used were 1% and 2%

Fig. 5 CBR test on treated sand samples

(a) Photograph



(b) Schematic view for the detail configuration

Fig. 6 Wind tunnel for wind erosion tests

of the water amount (1 L). Pure (without any additive) and water-treated (1 L of water was sprayed on the sand) sand specimens were prepared for comparison with the serish-treated samples. For serish-treated samples, the solution of water and serish was prepared and sprayed evenly over the surface of the soil using bottles with a trigger sprayer. The amount of spraying was 1 L for a single specimen condition, where the solution concentrations (i.e., serish content to the mass of water) were 1% (10 g) and 2% (20 g). The serish-treated samples were maintained at room temperature (20ºC) for 1day prior to testing (Kavazanjian Jr *et al.* 2009). Aluminum trays and a ductwork with the output span of 42 cm × 42 cm and a length of 140 cm (Fig. 6) were used for this purpose.

The average speed of wind in the desert area is approximately 7 m/s (Alamdari *et al.* 2012); thus, an industrial stand fan (Industrial Plate mounted Flow Fan, Ilka Model-Metalic Propeller) with the capability of producing 8±0.3 m/s was used. To reach a laminar flow, five turbulent grids (or nets with a single cell of 1 mm × 1 mm × 1 mm) were placed with 10 cm spans and the wind speed was controlled at 8±0.3 m/s along the entire tunnel

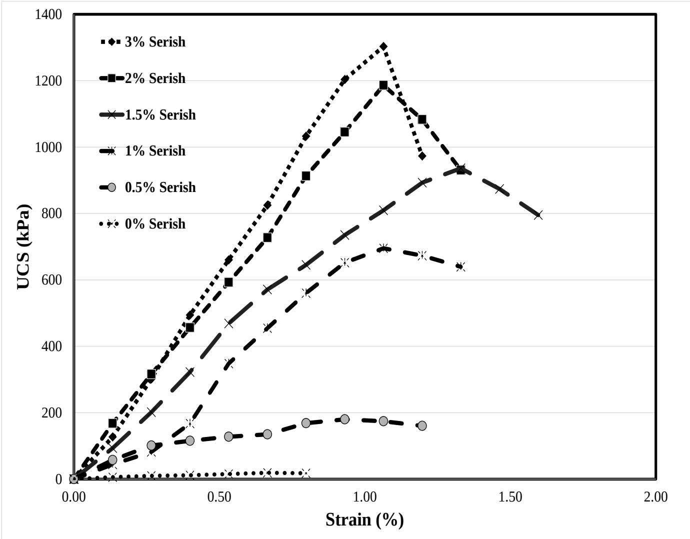


Fig. 7 Stress – axial strain curves of tested samples obtained via unconfined compression test

Table 2 Specimen conditions and experimental program

Experimental program	Biopolymer content (%)	Drying time (days)
Unconfined compression test	0, 0.5, 1, 1.5, 2, 3	7
	2	1, 3, 7, 14, 28
California bearing ratio test	0, 1, 2	7
Wind erosion test	0, 1, 2	1
Scanning electron microscopy	1, 2	7

(Kuttarmare *et al.* 2014, Bahmani *et al.* 2019). As shown in Fig. 6, the specimen pan was located at 0.5 m from the first turbulent grid and subjected to airflow for 10 minutes. The difference in the weight of sand pans before and after the wind erosion test showed the amount of soil loss. Three repetitions were performed for each test.

2.3.5 SEM observation

In order to observe and analyze the microscale inter-particle interaction between serish and soil particles, SEM images were used. For this purpose, serish-treated dune sand with 1% and 2% of serish content was selected. After drying the samples, to avoid electron scattering, their surfaces were coated with Au. It is worthy to note that the images were taken by a scanning electron microscope (Tescan VEGA-II).

The overview of the experimental program and specimen conditions (biopolymer content and drying time) are summarized in Table 2.

3. Results and discussion

3.1 Unconfined Compression Strength (UCS)

The effects of serish content and drying time were investigated by the UCS test. The stress-strain behavior graphs of the treated and untreated sand samples after 7 days of drying are represented in Fig. 7. According to Fig. 7, considering the strain levels at failure for treated samples, samples with 3% and 0.5% of serish showed a brittle behavior compared to others. The higher failure strain in the samples treated with 1.5% of serish can be attributed to pore filling effect of biopolymer hydrogel; however, by adding more (2% and 3%) serish, the stress-strain behavior became brittle compared to soil treated with 1.5% of serish (Fig. 7).

Fig. 8 illustrates the UCS variation of the treated and untreated dune sand in terms of biopolymer contents, after 7 days of drying. As seen, the compressive strength was significantly improved for the samples treated with serish. Untreated dune sand naturally demonstrates a very low compressive strength because of the negligible cohesion of sand grains. In this case, untreated sand showed UCS of 19.1 kPa. By adding 0.5% of biopolymer, the UCS increased to 180.3 kPa. Using 1% of serish, more enhancement was observed (695.2 kPa). A tendency towards enhancement in the UCS values was maintained by increasing the serish content up to 3%. This behavior can indicate that serish paste lies between the sand particles to bind them together, forming a bridge between the particles that leads to an increase in strength.

The drying time and accompanying moisture content are important factors affecting the strength of biopolymer-treated soils. To this end, 2% of serish was added to the sand samples and effect of drying time was evaluated in 1, 3, 7, 14 and 28 days. Due to the marginal changes observed in the UCS values, the tests were terminated after 28 days of drying time.

As summarized in Table 3, compressive strength was increased over time. Following 24 hours of drying, the UCS increased to 153.3 kPa. After 7 days, the compressive strength rose due to a significant reduction in moisture content, reaching 93 percent of its ultimate UCS value. The increasing process continued up to 28 days; however, the growth rate was negligible after 1 week, and time did not dramatically change the structural alignment of the bio-treated soil matrix. As a result, 7 days of drying was regarded as the optimal time for serish-treated sand samples to achieve their final compressive strength. Table 3 also shows the variation of elastic modulus (E50), failure strain and water content in terms of drying time and serish content.

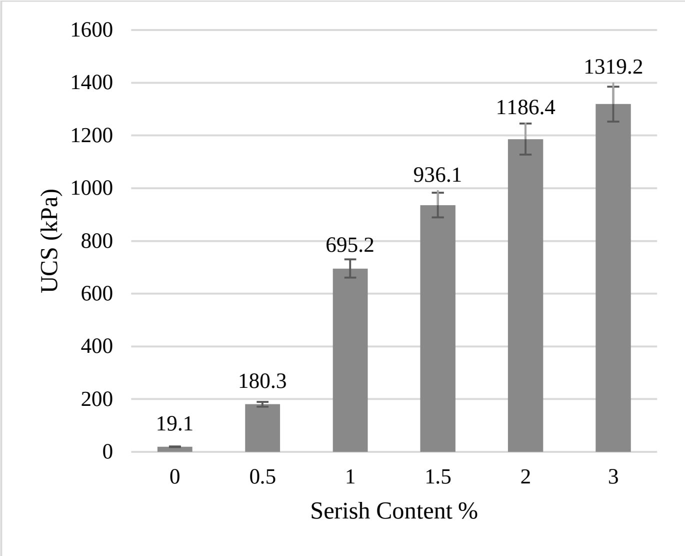


Fig. 8 The unconfined compressive strength variation with serish contents

Table 3 UCS, modulus of elasticity, failure strain and water content of the serish-treated samples over time

Drying time (days)	Serish content (%)	UCS (kPa)	E_{50} (MPa)	Failure strain (%)	Water content (%)
1	2	153.3	12.1	3.43	12.3
3	2	454.0	23.1	1.75	7.3
7	0	19.1	4.0	0.80	1.1
	0.5	180.3	38.0	1.21	1.1
	1	695.2	66.2	1.33	1.1
	1.5	936.1	88.1	1.60	1.1
	2	1186.4	110.2	1.32	1.2
	3	1319.2	135.1	1.20	1.1
14	2	1233.5	123.3	1.37	0.5
28	2	1274.4	118.0	1.29	0.2

The strengthening efficiency of serish treatment on the compressive strength of dune sand has been compared with other biopolymer-treated sands in Fig. 9. It can be observed that serish yielded a more significant performance than agar gum, casein, sodium alginate, as well as gellan. This is in the condition that xanthan gum showed the highest strength by a value larger than 1600 kPa, while the strength of serish-treated sand is around 1200 kPa. It should be noted that the sands utilized in Fig. 9 for various biopolymers may differ slightly from the dune sand used in this study (in terms of particle size, particle shape, and size distribution). Although it is still a long way to deeply understand the serish performance in soil treatment, the results show a great potential in serish to be employed as a binder in geotechnical applications.

3.2 California Bearing Ratio (CBR)

In designing pavement layers, one of the main factors is CBR strength. Therefore, the unsoaked CBR tests were conducted on natural dune sand and biopolymer-treated sand samples. Fig. 10 indicates the strength of the samples under penetration (Fig. 10(a)) and the average CBR values obtained from the stress-penetration graphs (Fig. 10(b)).

As it can be seen from Fig. 10(b) by adding 1% of serish to the sand, there was a remarkable growth in the CBR value from 19.68% for the pure sand to 96.54% for the serish-treated sand. In case of 2% of serish, CBR increment continued by reaching 177.85%. The CBR values of the treated soil with 1% and 2% of serish were 4.9 and 9 times higher than the natural sand, respectively. The increase of the CBR strength causes enhancement in the resilient modules of the subbase and base layers, which leads to a reduction in pavement layers. This improvement stems from the formation of more resistant bonds between soil grains and serish.

3.3 Wind erosion test

A wind erosion experiment was designed to investigate the wind erosion resistance of the serish-treated sand (Fig. 11). The results are presented in Table 4. According to the results, natural sand and water-treated sand are vulnerable to wind erosion considering the reduction in the weight of the samples observed after 10 minutes of wind blowing. As a result of sand stabilization, the wind erosion resistance

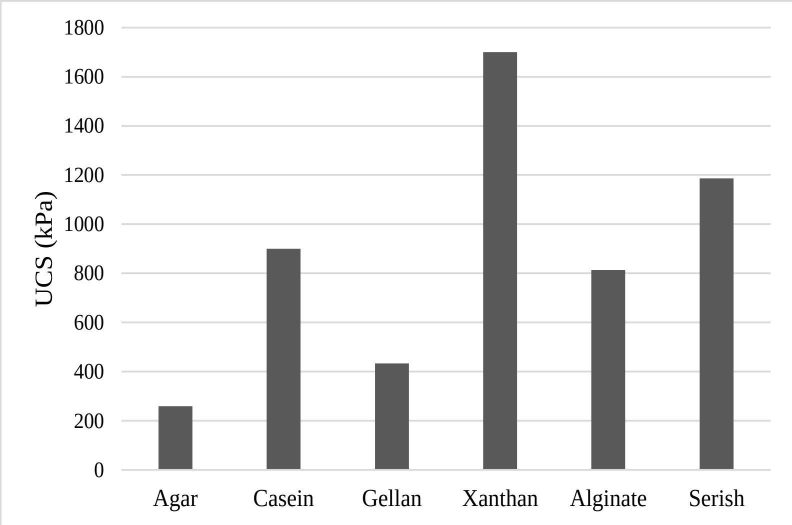
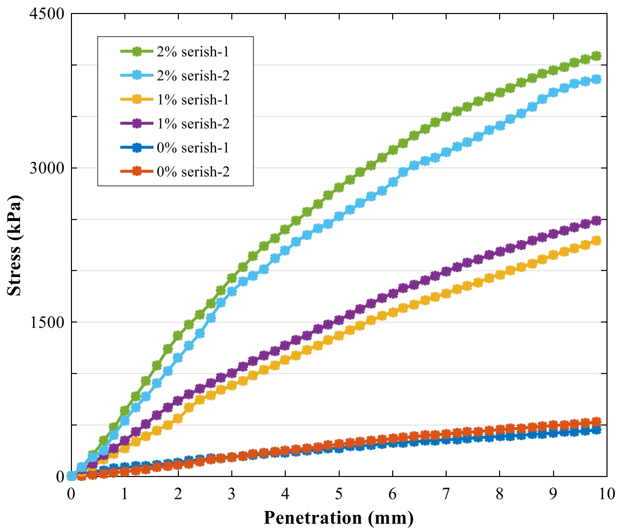
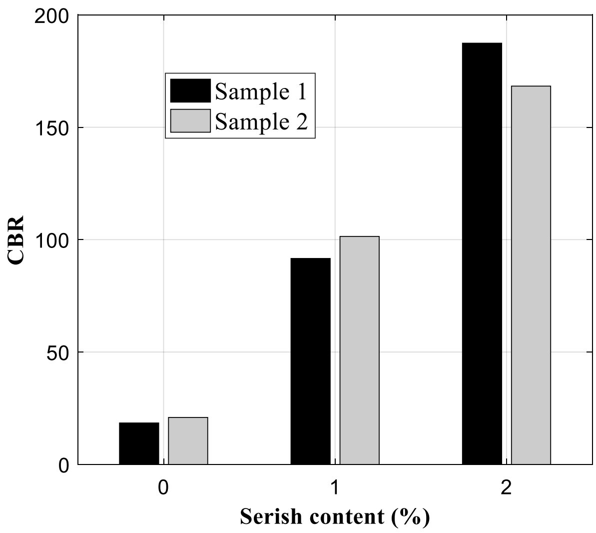


Fig. 9 Maximum UCS value of treated sand with 2% of different biopolymers (Khatami and O'Kelly 2013, Chang *et al.* 2015, Chang *et al*. 2016, Fatehi *et al*. 2018, Fatehi *et al.* 2019, Fatehi *et al*. 2021)



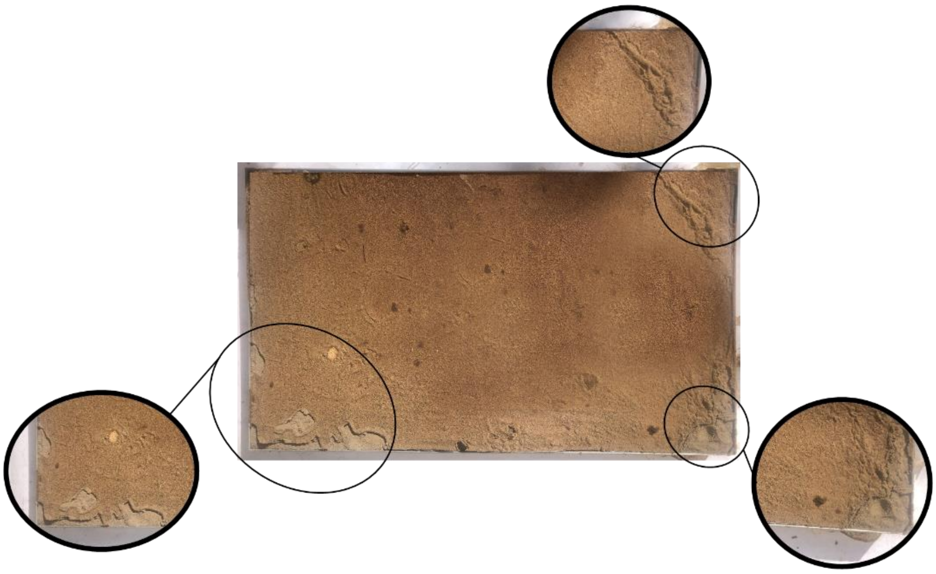
(a) Stress-penetration curves



(b) CBR values

Fig. 10 CBR test results for 0%, 1%, and 2% serish-treated sands

(a) Before the experiment.



(b) After the experiment

Fig. 11 Serish-treated sand sample for the wind erosion test

significantly improved by losing less than 1.21% soil for 2% serish-treated sand. Moreover, it should be kept in mind that typically water must be applied repeatedly to the soil to maintain its effectiveness as a wind erosion (dust) control measure, particularly in arid and semi-arid climates. The high amount of eroded sand in the samples without additive is due to the low shear strength and lack of cohesion between sand grains. By improving particles interactions and shear strength over the soil surface, stronger resistant forces are gained against driving forces so that less soil is eroded by adding serish. Formation of a crust on the treated samples seems to be the main mechanism by which the wind erosion resistance is improved by biopolymer emulsion (Kavazanjian Jr *et al.* 2009).

3.4 Microscopic observation

SEM images were used to microstructurally observe the interaction between sand and biopolymer in order to gain a better understanding of the underlying stabilizing mechanism. These images were captured using 1% and 2% serish-treated samples with different magnifications after the unconfined compression test; the images are presented in Fig. 12. Generally, in the natural state of dune sand, particles have a relatively rounded shape and smooth surface with no adhered materials and are separate from each other; therefore, there is no bonding among them (Wang *et al.* 2018). In addition, the equal size of particles and their rounded shape cause them to move on each other with no restriction due to the lack of cohesion. Also, through their existing pores, dust particles separate from the soil body and freely scatter to the air. While, as shown in Fig. 12, in treated samples the pore space between the sand

Table 4 Performance of treated and untreated sand under wind erosion test

Sample	**Normalized application rate of biopolymer (g/m2)**	**Loss after 10 minutes of blowing (%)**
Natural sand	0	38.3
Water treated sand	0	26.07
1% serish	43.8	2.63
2% serish	87.5	1.21

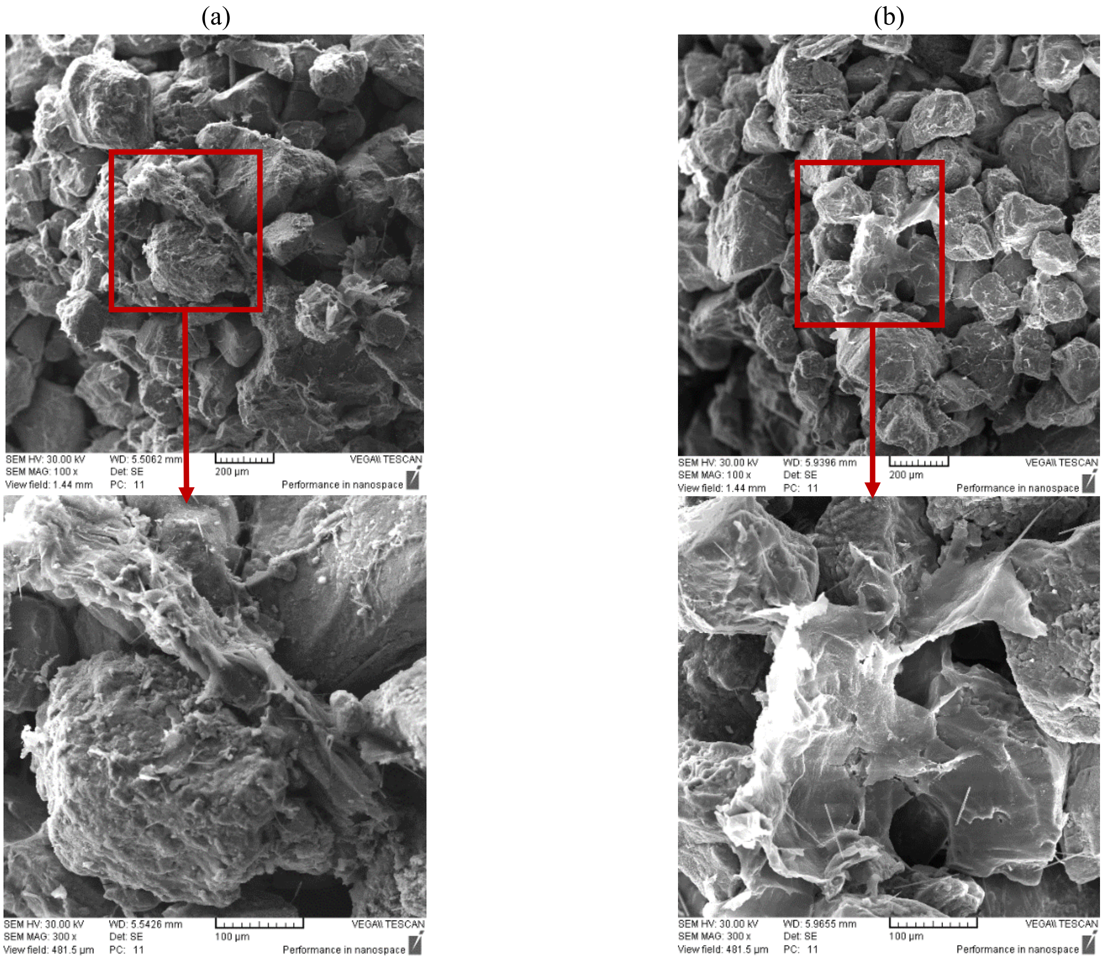


Fig. 12 SEM images of the specimens with (a) 1% and (b) 2% of serish

particles became smaller and the surface of the sand particles was rough. The paste, obtained from dissolving serish in water, causes sand particles to stick together as a whole soil body. It can also be seen, that particle surfaces coated by serish paste increase contact surfaces between soil particles. Increasing the serish concentration from 1% to 2% results in a higher amount of paste coating grain surfaces, covering more particles and increasing the contact surfaces between soil particles. This process creates a stronger soil body with higher UCS and CBR values.

Based on the previous studies, biopolymers have shown remarkable strengthening qualities due to the direct ionic bonding, hydrogen or electrostatic bonding, and continuous biopolymer matrix formation between biopolymers and soil particles (Chang *et al.* 2015). Generally, biopolymers lead to increased cohesive forces within the soil matrix. In the serish-treated sand, this strengthening arises from the amount of polysaccharides, which are abundant in the root of the Eremurus plant (Pourfarzad *et al.* 2014).

3.5 Economic/environmental efficiency

Uniaxial compressive strength tests were carried out using dune sand treated with 8% of Ordinary Portland cement. According to Fig. 13, compared to cement, the UCS values of the serish-treated sand were higher when the serish content was 2%. The difference between strengths was even more when cured for 7 days.

Generally, cement is much less expensive than biopolymers. However, because soil-cement requires more cement than soil-serish (serish to soil ratio in mass < 3%), material cost for soil stabilization will reduce the price gap between cement and serish. For a unit amount (1 ton) of soil treatment, in terms of the pure material price, serish is inadequate for replacing the role of ordinary cement treatment (9.92 USD to 10.26 USD). However, by considering the carbon emission and environmentally friendly factors, results become interesting. Cement production leads to greenhouse gases emission. The amount of CO_2 emitted (the total indirect environmental impact) by 1 ton cement production is 1.25 ton (Chang *et al.* 2016), while serish is anticipated to be significantly environmentally friendly due to its origin (plant-based biopolymer which fixates abundant amount of CO_2). This can add up to a costly treatment of soil using cement considering carbon emission trading (Chang *et al.* 2016) or social cost of carbon (SCC). The SCC is a widely used methodology for estimation of the economic damages that would result from emitting one additional ton of CO_2 into the atmosphere each year. The SCC puts changes such as human health, property damages due to increased flood risk,

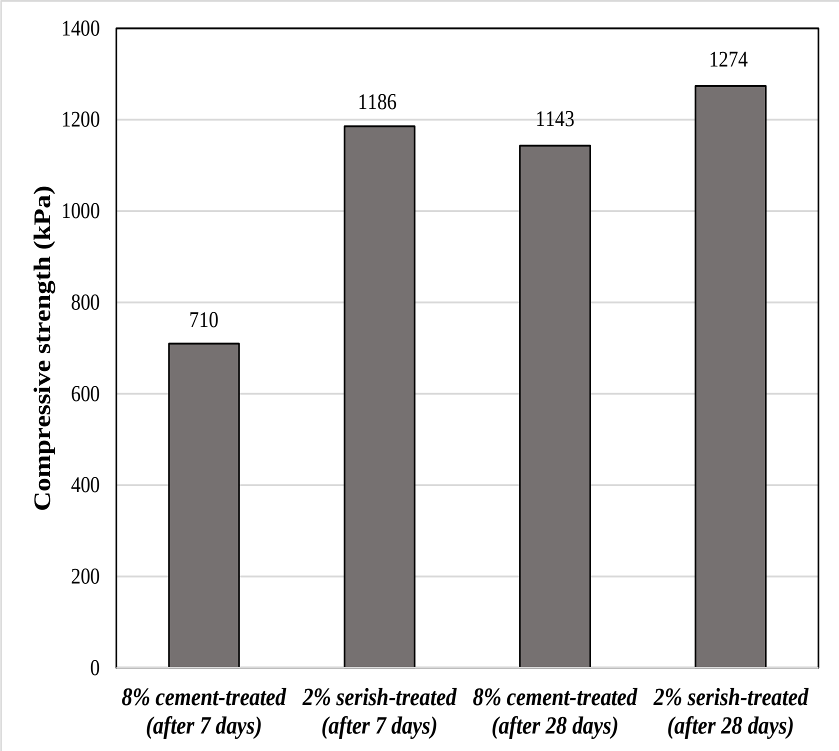


Fig. 13 Comparison of compressive strength of serish-treated sand to that of 8% cement-treated sand (after 7 and 28 days)

Table 5 Economic analysis of Ordinary Portland cement and serish

Material	Ordinary Portland cement	Serish
Market price	124 USD/ton[a]	513 USD/ton[b]
Required amount for 1 ton soil treatment (ton)	0.08	0.02
Material cost for 1 ton soil treatment (USD)	9.92	10.26

[a] Represents the price of cement in the United States, in 2020 (www.statista.com).
[b] Represents the price of serish (www.ganjkala.ir).

net agricultural productivity and the value of ecosystem services caused by climate change, into economic terms to aid policymakers and other decision-makers in understanding the financial consequences of decisions (Shindell 2015, Resources for the Future 2021). The SCC value for an average discount rate of 3% in 2020 was \$50/ton CO2 (Resources for the Future 2021). However, for obtaining the CO_2 amount consumed or emitted by serish production in large scale, a comprehensive study is needed.

Considering the SCC, the high amount of CO_2 emitted by cement, and the slight difference between material price of cement and serish for 1 ton soil treatment (according to Table 5), serish biopolymer is able to be more economically feasible with far less environmental repercussions. Also, the serish treatment can result in enhanced engineering performance compared to cement treatment; however, there is still a long way ahead of using serish in practical applications and more studies need to investigate various aspects of serish-treated soil.

4. Conclusions

The initial goal of this study is to establish the serish powder obtained from the *Eremurus* plant as an additive for soil improvement. This polymer-based material is biodegradable and possesses environmentally-friendly factors for soil treatment purposes. In order to investigate the role of serish in enhancing the geotechnical behavior of dune sand, a series of laboratory experiments was carried out. The uniaxial compression tests were conducted to investigate the influences of the biopolymer content and drying time on the compressive behavior of the dune sand. The results indicated that the uniaxial compressive strength and elastic modulus of the sand improved when the serish content increased. As the drying time increased, the moisture content reduced and led to a considerable rise in unconfined compressive strength. Moreover, serish-treated sand reached more than 90% of its final compressive strength in 7 days of drying.

CBR tests were conducted on serish-treated sand samples, dried for 7 days at room temperature. CBR values showed a significant improvement for serish-treated sand compared to its untreated state. CBR values of the treated sand with 1% and 2% of serish were 4.9 and 9 times higher than natural sand, respectively. Furthermore, a wind erosion test was performed to provide a better understanding of the serish role in wind erosion resistance of the treated sand. Results showed that serish is able to perform as a stabilizing agent against erosion induced by wind. The results obtained from the wind erosion test demonstrated promising improvement. The amount of soil loss after 10 minutes of wind blowing was only 2.63% and 1.21% for 1% and 2% of serish, respectively, compared to the soil loss for natural

(38%) and water-treated sand (26%). Also, the serish and sand interaction was analyzed using SEM images. The SEM images illustrated that biopolymer provided a bridge that bonded soil particles together. Additionally, for economic/environmental efficiency, the serish treatment becomes a potential option that could take the place of the less environmentally-friendly cement, especially in terms of the amount of CO_2 emission. However, further investigation to evaluate various aspects of utilizing serish additive is required.

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