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Stabilization of sand with combined use of lignosulfonate and polyethyleneimine: Water resistance and mechanical properties of treated sand

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Abstract. Lignosulfonate (LS), an environmentally friendly and non-toxic material, has attracted attention as a non-traditional soil stabilizer. However, LS could be easily washed out from soil due to its high water-solubility, which leads to the consequent loss of strength. Therefore, an additional admixture is needed to overcome this limitation. In this study, polyethyleneimine (PEI) was mixed with LS to stabilize silica sand. The consequent improvements in the water-resistant and strength characteristics of LS-treated soil were investigated through the unconfined compressive strength (UCS) test, triaxial test, and cyclic wetting-drying tests. The results demonstrated that the UCS had an increasing trend with a rise in LS content. Moreover, the UCS was influenced by the drying out of the water from the specimen related to the LS concentration and the curing time: a higher concentration and a longer curing duration improve the UCS. According to the triaxial test, the deviatoric stress also increased with the LS content. In addition, both the soil's cohesion and secant elastic modulus were improved in a more ductile manner than typical cemented soil. In the cyclic wetting-drying test, no disintegration of the specimen was observed. Although the UCS of the treated soil in wet condition revealed a notable decrease, after re-dry for seven days in a controlled room, its strength recovered to about 86% of that in its initial dry condition.

Keywords: lignosulfonate; polyethyleneimine; unconfined compressive strength; wetting-drying cycle

1. Introduction

Transportation geosystems often experience a wide range of traffic loads. From the particle scale point of view, stress concentrated at grain contacts produces fines and may trigger the undrained failure of railway ballast (*Indraratna et al.* 1997). Geomaterials used for sublayers also exhibit remarkable features of plastic strain accumulation when subjected to traffic loads. Unfortunately, transportation-related construction projects are exposed to geomaterials with low strength and high settlement that affect the long-term performance, serviceability, and safety. In fact, construction in soft and low shear strength soil is still one of the most challenging obstacles in the field of geotechnical engineering due to the insufficient bearing capacity, excessive post-construction settlement, and instability on excavation and embankment formation (Mohamad *et al.* 2016). In this context, chemical stabilization appears to be a good method to improve the geotechnical soil properties such as soils, rock mixtures and recycled granular materials (Ta'negonbadi and Noorzad, 2017). Soil stabilization is an economical and enduring method for attaining the desiderated geotechnical properties to solve these problems. Previous research over the last few decades have used cement, lime, gypsum, slag, and fly ash in attempts to enhance the workability and shear strength of soil (Ansary *et al.* 2007, Bhurtel and Eisazadeh 2020, Celik and Nalbantoglu 2013, Chew *et al.* 2004, Degirmenci *et al.* 2007, Lee *et al.* 2019, Osinubi 2006). Nevertheless, to reduce the drawbacks of the conventional methods and provide sustainable development, other new materials have been continuously investigated.

Lignosulfonate (LS), a type of lignin and an industrial by-product of the sulfite pulping process, is increasingly utilized in engineering and science applications. In

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particular, the functionalization of the lignin hydroxyl group is suitable for building block units in material science such as polymer syntheses, carbon fibers, or thermoplastic polymer (Laurichesse and Avérous 2014). Lignin could be a renewable feedstock to substitute synthetic phenols in binders or phenol-formaldehyde resins and beneficial to wastewater treatment because of its high adsorption capacity and affinity, contributing to the treatment of heavy metals (Naseer *et al.* 2019). Furthermore, LS is applied as a water reducer for concrete admixtures due to an anionic surface-active polymer capable of exerting electrostatic repulsion and steric hindrance (Huang *et al.* 2019). Lignin also improves fluidity and induces an effective dispersion of cement paste (Lou *et al.* 2013, Mullick 1996, Sutradhar *et al*. 2023, Zhong *et al.* 2022).

LS not only offers benefits in scientific and engineering fields but also play a critical role in geotechnical engineering, especially in enhancing soil properties. For example, LS could be used as dust suppressants since it has the ability to bind soil particles together through its combination of chemical and physical interactions (Gebhart *et al.* 1999, Withycombe and Dulla 2006). Furthermore, LS could improve soil mechanical strength; for example, it helps reduce the erosion rate as it prevents the penetration of flow into soil particles by creating a polymer chain between the particles and leading the soil particles neither to be dislodged nor to move rapidly (Koohpeyma *et al.* 2013). LS stabilizes expansive soil and promotes UCS and shear strength of soil due to its physical and chemical interactions (Addo *et al.* 2004, Chen and Indraratna 2015b, Ta'negonbadi and Noorzad 2017, Zhang *et al.* 2018). LS-treated specimens have higher ductility in comparison to conventionally-treated specimens. LS stabilizer does not contain any toxic substances such as formaldehyde, a harmful chemical compound for life and environment (Mitchell and Soga 2005, Rollings *et al.* 1999, Vinod *et al.* 2010). In addition, LS is an environmentally friendly stabilizer due to the fact that it does not produce CO_2 gas or corrosive environment [pH < 12.5 - Zhang *et al.* (2019)]. Therefore, industrial by-products (i.e., lignosulfonate) have increasingly attracted attention due to their economical and environmentally friendly aspects (Chen and Indraratna 2015a, Enayathali and Nachiappan 2024, Indraratna *et al.* 2008, Khajeh *et al.* 2024, Zhang *et al*. 2018).

Moreover, associated examples for LS-treated soils involve that: increased dry density with a lower optimal moisture content (Lu *et al.* 2023), density and strength improvement in unpaved roads (Barbieri *et al.* 2020), decreased plastic strain accumulation and excess pore water pressure under cyclic loadings in railway systems (Roshan *et al.* 2022), increased bearing-capacity (Fernandez *et al.* 2021), and decreased swelling extent in particular for expansive soils (Alazigha *et al.* 2018). Indeed, the use of industrial by-products such as LS enhances not only the performance and durability of geomaterials in transportation geosystems but also contributes to sustainable engineering practices. Leveraging these by-products allows for the enhancement of soil properties and long-term stability in infrastructure, while also contributing to reduced environmental impacts and increased resource efficiency.

Although LS offers the aforementioned benefits, it has a limitation in water resistance due to its hydrophilic groups, which can leach out over time. This leaching effect may lead to a reduction in strength and make it less suitable for applications requiring extended curing periods (Geng and Li 2006, Kim *et al.* 2012, Ravishankar *et al.* 2017, Ta'negonbadi and Noorzad 2017). Thus, an additional admixture is required to overcome the deficiencies of LS.

In this study, a series of comprehensive laboratory experiments were performed to explore the applicability of LS to soil stabilization. Polyethyleneimine (PEI), a polymer consisting of the repeat amine group and two aliphatic carbons (Vancha *et al*. 2004), was introduced as a new additive for LS-stabilized soil. Unconfined compressive, triaxial, and cyclic wetting-drying tests were conducted to explore mechanical strength and water resistance improvements of the new LS-PEI adhesive.

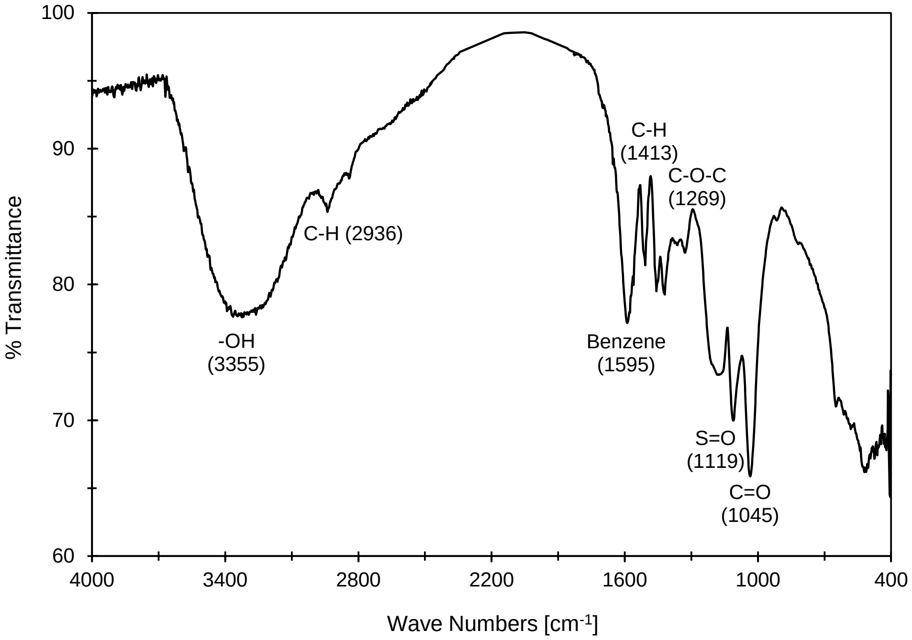
2. Experimental program

2.1 Materials

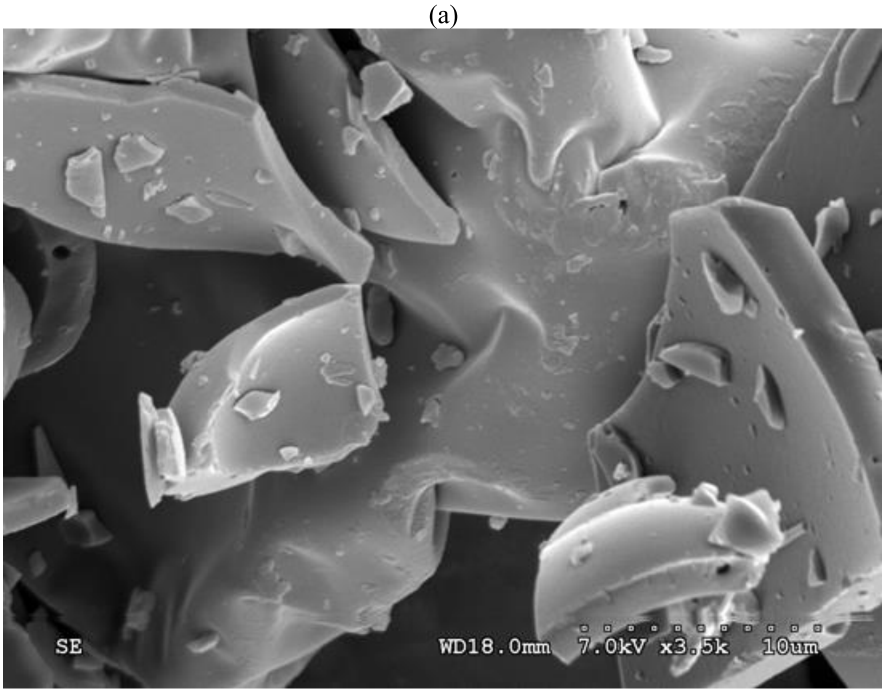
Crushed silica sand (K5, Kyung In Co., South Korea) was used as the primary material in the experiments in this study. The tested sand was classified as poorly graded sand (SP) according to the Unified Soil Classification System (USCS) with a median particle size (D_{50}) of 0.55 mm. The specific gravity (G_s) was measured as 2.66. The minimum and maximum void ratios (e_{min} and e_{max}) were 0.688 and 1.071, respectively.

Lignosulfonate (LS) is an anionic polyelectrolyte polymer with high water solubility (Huang *et al.* 2019). LS (B&B company, South Korea) is a yellow-brown powder with a fragrant smell. Its average molar mass is about 50,000 g/mol, and its polydispersity is from 6-8 (provided by the manufacturer). It is known that LS dissolves in deionized water as well as alkaline and acidic solutions. Fig. 1 shows a functional group of LS detected by Fourier transform infrared resonance (FTIR) spectroscopy (Agilent Cary 630 FTIR) and the surface morphology of LS detected from the scanning electron microscopy (SEM) (Hitachi S-4300). LS consists of functional groups such as a hydroxyl group, -OH (3355 cm^{-1}), a C-H stretching group (2936 and 1413 cm^{-1}), a benzene ring (1595 cm^{-1}), and a S=O stretching sulfonate group (1119 cm^{-1}). Additionally, the SEM image reveals that LS has an amorphous shape with smooth surface layers.

Polyethyleneimine (PEI, Wako Chemicals, Japan) used in this study is a highly branched polyamine with a high cationic charge density. It contains primary, secondary, and tertiary amine groups in an approximate ratio of 25/50/25, respectively. PEI is a colorless and clear liquid with a density of 1.03 g/cm^3, and its molecular weight is 70,000 g/mol with a concentration of 30% (provided by the manufacturer). Its viscosity varies from 0.4 Pa.s to 0.9 Pa.s at 25.0 ± 0.5^{o}C. Moreover, it is completely dissolved in deionized water as well as in alkaline and acidic solutions.



(a)



(b)

Fig. 1 Properties of lignosulfonate: (a) functional groups by FTIR and (b) surface morphology by SEM

2.2 Sample preparation

In this study, before preparing the samples, K5 sand was dried in a convection oven at 105°C for 24 hours. LS was then dissolved in deionized water at various concentrations, as shown in Table 1. These various LS concentrations were prepared to evaluate the workability of the stabilizer and its effectiveness in improving the engineering properties of the treated soil. In addition to LS concentration, the PEI ratio plays a critical role in enhancing the durability of the treated specimens by increasing their water resistance. Thus, after LS was fully dissolved, PEI was added to the solution in varying mass ratios, as detailed in Table 1. The mixture was mechanically stirred for 2 minutes using an overhead blender to ensure homogeneity. The binder solution was then poured into the dried K5 sand with varying LS contents to evaluate the impact of the LS-PEI stabilizer on the treated specimens' improvement. The mixture was mechanically blended for 10 minutes using an overhead blender. Specimens with different LS concentrations and contents were prepared for each experiment, as outlined in Table 1. Note that the specimens were prepared with different LS concentrations and LS contents, as shown in Table 1, for each experiment.

Table 1 Summary of specimen combinations

Test	Category	Sand (DR %)	LS Content (%)	LS Concentration (g/mL)	PEI:LS	Curing
Water Susceptibility		50	5	1.00	0; 0.25; 0.50; 0.75; 1.00; 2.00	Humidity 40% Temp. 20°C Time 24 hours
UCS	A: LS concentration	50	10	0.50; 0.75; 1.00; 1.25; 1.50	1:1	Humidity 40% Temp. 20°C Time 7, 14, 28 days
	B: LS content	50	0; 5; 8; 10; 12	1.25		
Wetting-Drying Cycle		50	10	1.25	1:1	Humidity 40% Temp. 20°C Time 7 days
Triaxial		50	0; 5; 8; 10; 12	1.25	1:1	Humidity 40% Temp. 20°C Time 28 days

$$\text{LS concentration} = \frac{mass\ of\ LS}{mass\ of\ water} \tag{1}$$

$$\text{LS content (\%)} = \frac{mass\ of\ LS}{mass\ of\ dry\ sand} \times 100 \tag{2}$$

Two groups of specimens were prepared with different shapes and sizes for the different experiments: group 1) water susceptibility, UCS and wetting-drying cyclic tests and group 2) triaxial tests. For the group 1, the mixture was poured into a cubic mold with dimensions of 50 mm × 50 mm × 50 mm, while for the group 2, the mixture was poured into a cylindrical mold with a diameter of 50 mm and a height of 100 mm. All specimens were lightly compacted to achieve a relative density of 50% using a tamping rod, in accordance with the compaction method outlined in ASTM D5102. Specimens were removed from the mold after one day and cured in an incubator (i.e., a temperature of 20°C and a humidity of 40%), similarly to room conditions for the duration of the predetermined curing period.

2.3 Experimental programs

The water susceptibility test was conducted to determine the amount of PEI needed to improve the water resistance of the LS-treated soil. The specimens were composed of six different mass ratios of PEI:LS (0:1, 1:4, 1:2, 3:4, 1:1, and 2:1) as outlined in Table 1, and all were demolded after one day and immediately soaked into a water tank at room temperature.

It is known that viscosity influences the workability of soil stabilizers: the higher the viscosity, the lower the workability (Ferraris and Martys 2003, Hočevar *et al.* 2013). Therefore, the viscosity of the LS-PEI solution was measured to assess the workability of the binder using a rheometer (Brookfield, RST-SST) with a four-blade vane spindle (VT-80-70; vane height = 80 mm and vane blade width = 35 mm). The specimens were composed of a wide range of LS concentrations from 0.25 g/mL to 2.00 g/mL. The viscosity of each combination is defined by the value at their equilibrium states at the high shear rate (Brunn and Vorwerk 1993).

To evaluate the improvement in the compressive strength of the LS-treated sand in a laboratory, the UCS test was conducted in accordance with ASTM C109 using a universal testing machine (HS-1470, Hanshin). The following two factors were selected as test variables for the UCS test: 1) effect of LS concentration (Eq. (1)) and effect of LS content (Eq. (2)). The applied strain rate was fixed at 1 mm/min. Triplicate samples were tested, and the average peak normal stress of the stress-strain curves was determined to be the specimen's UCS.

The consolidated undrained triaxial test was performed following ASTM D4767 to analyze the effect of the LS content on the shear strength parameters and behaviors of the treated specimens. The specimens were cured in a controlled environment (i.e., an incubator) for 28 days. To ensure proper saturation before testing, the B-value, also known as Skempton's coefficient, which measures the degree of saturation of the soil sample, was employed. Consequently, the specimens were saturated to achieve a B-value greater than 0.95 in the triaxial testing chamber prior to testing. The confining stresses of the experiment were 100, 200, and 300 kPa. The loading rate was fixed at 6% per hour, and the test was completed when the axial strain reached 25%.

The methodology for the cyclic wetting-drying test was adapted from the procedures outlined by Rogers and Wright (1986) and Ta'negonbadi and Noorzad (2017), which describe similar wetting and drying protocols used in durability studies of chemically stabilized soils. This test was performed to investigate the moisture susceptibility of specimens treated with PEI additives and to determine the UCS over four cycles of wetting and drying sequences, as detailed in Table 2. After seven days of curing in the controlled room, all specimens were fully submerged into deionized water at room temperature for 24 hours. Then some specimens were randomly selected to measure UCS, while others were reposited into the controlled room to dry for the following cycles. After seven days of drying, randomly selected specimens underwent UCS tests. This process was repeated continuously until the completion of the fourth cycle. Note that

Table 2 Order of experimental wetting-drying testing condition

		1st Cycle	2nd Cycle	3rd Cycle	4th Cycle
Initial	1 ↘				
Soaking		2 ↓ ↗	4 ↓ ↗	6 ↓ ↗	8 ↓
Drying		3	5	7	9

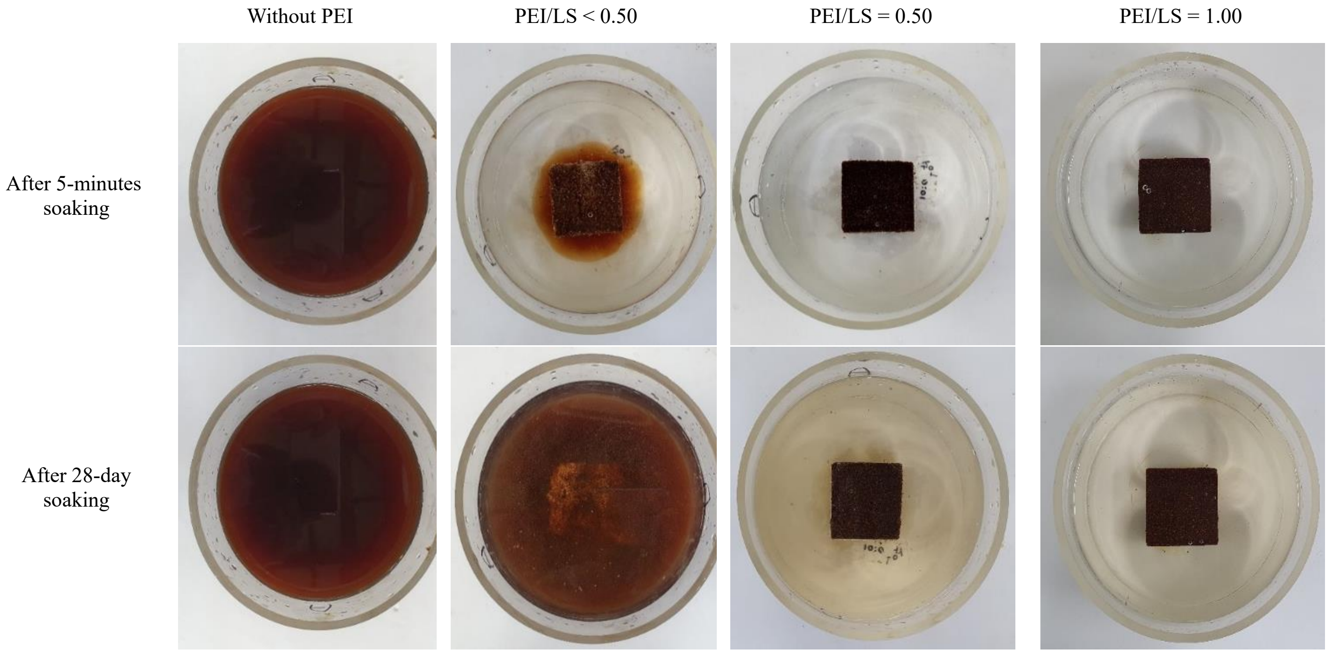


Fig. 2 Water resistance of lignosulfonate (LS)-polyethyleneimine (PEI) treated sand as a function of PEI/LS

the specimens for the cyclic wetting-drying test were replicated in an optimal combination for the UCS test, as described in Table 1, and for all tested specimens, the changes in mass were monitored to demonstrate the water resistance due to soil disintegration.

3. Experimental results

3.1 Effect of PEI on water susceptibility of LS treated soil

In addition, PEI has played a significant role in promoting the water resistance of LS-treated soil. As shown in Fig. 2, the specimen could disintegrate when there is an insufficient PEI. For example, the specimens composed of PEI:LS < 1:2 (i.e., PEI/LS < 0.5) break down into the water, and the LS leaches out of the specimen into the water, while the specimens composed of PEI:LS ≥ 1:2 (i.e., PEI/LS≥0.5) do not show any disintegration into the water within 28 days. As a result, the PEI:LS ratio is fixed at 1:1 and applied in the other experiments in this study.

3.2 The viscosity of the LS-PEI binder

Fig. 3 shows the measured viscosity of the LS-PEI binder according to LS concentrations. The viscosity increment of the LS-PEI binder shows two distinguished trends with increasing LS concentration: the increment of viscosity increases gradually for the cases with a concentration of less than 1 g/mL, whereas it increases sharply for cases above 1 g/mL. Since the measured viscosity of the LS-PEI binder with a 1.5 g/mL concentration exceeds the upper limit of the viscosity of cement slurry suggested by Zhang *et al.* (2019), the LS concentration in this study is selected to be less than 1.5 g/mL, based on considerations of workability.

3.3 Unconfined compressive strength of LS-PEI treated soil

Fig. 4 shows the variation in the UCS values among the treated specimens due to the LS concentration while maintaining the LS content of 10% with different curing times. With the same curing time, the UCS increases with an increase in the LS concentration: after curing for 28 days, the UCS values of the specimens with concentrations of 0.50, 0.75, 1.00, 1.25, and 1.50 g/mL are 4.01, 4.74, 4.82, 5.19, and 5.71 MPa, respectively. Furthermore, the UCS of those combinations composed of lower LS concentrations (i.e., 0.50, 0.75, and 1.00 g/mL) increases whereas, the UCS values for higher LS concentrations (i.e., 1.25 and 1.50 g/mL) remain at similar values with different curing times. This observation reveals that the strength of the treated specimen is primarily influenced by the adhesion of the binder mixture rather than

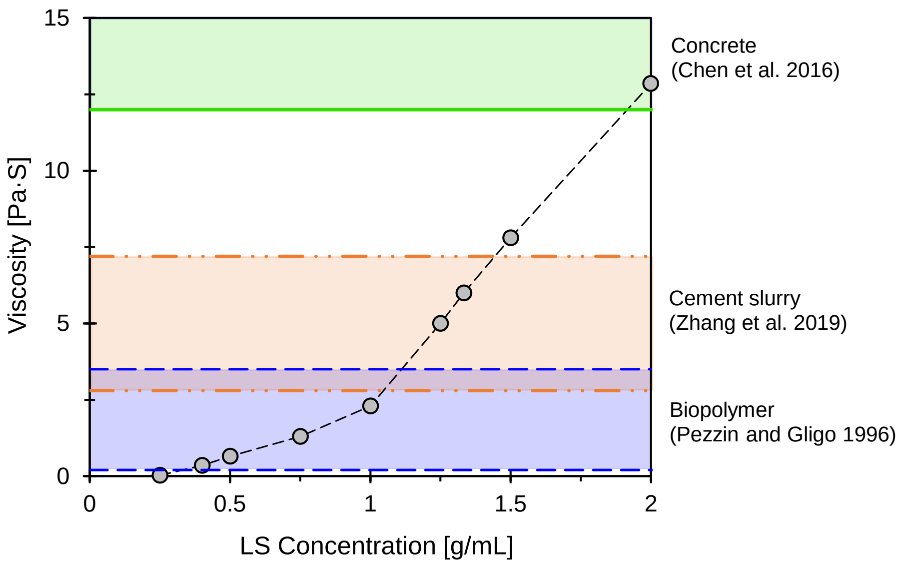


Fig. 3 Viscosity of LS-PEI binder according to LS concentration

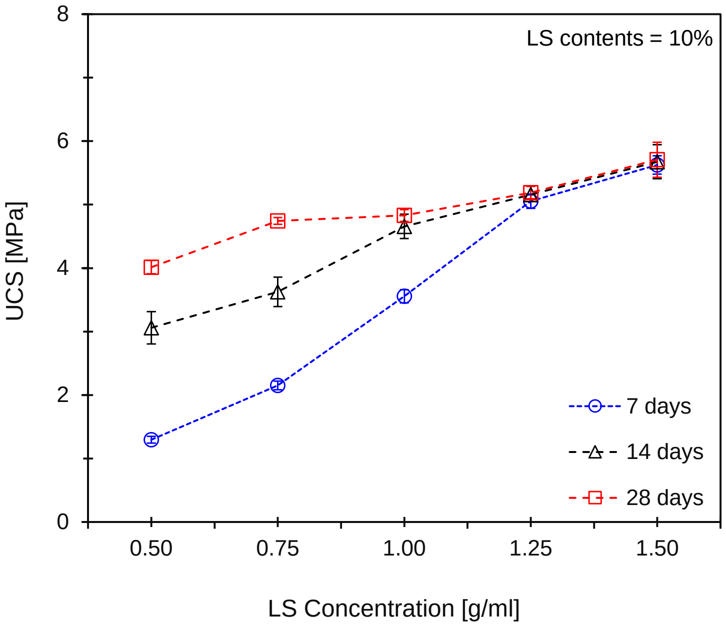


Fig. 4 Variation of unconfined compressive strength of tested materials with varying curing times according to LS concentration

the suction effect in the specimen because the lower LS concentration specimen could reach its dry condition more slowly compared to the higher LS concentration specimen, and no strength changes are observed for the higher LS concentration specimens with the curing time (Chen *et al.* 2019). As shown in Fig. 5, the LS-PEI adhesive in the specimen with a lower concentration of LS is relatively thicker than the higher concentration specimen and that the thickness of the lower concentration specimen decreases with curing times while that of the higher concentration specimen remains unchanged within the curing period.

Fig. 6(a) shows the effect of the LS content on the UCS of the treated soil. Note that the LS concentration of specimens was fixed as 1.25 g/mL. The UCS of the tested specimens increases with higher LS content. Specifically, the UCS values increase from 3.28 MPa at 5% LS content to a peak of 5.05 MPa at approximately 10% LS content across all curing durations. This indicates that LS content plays a crucial role in enhancing the strength of the treated specimens, as evidenced by a 54% increase in UCS when the LS content was raised from 5% to 10%. As shown in Fig. 6(b), the SEM images reveal that the specimen treated with LS content = 5% shows emptier void and fewer bonds than the 10% treated specimen.

The increase in LS content results in denser compacting cementation formed by the physiochemistry reactions between the LS and the sand particles. However, there is a drop in the

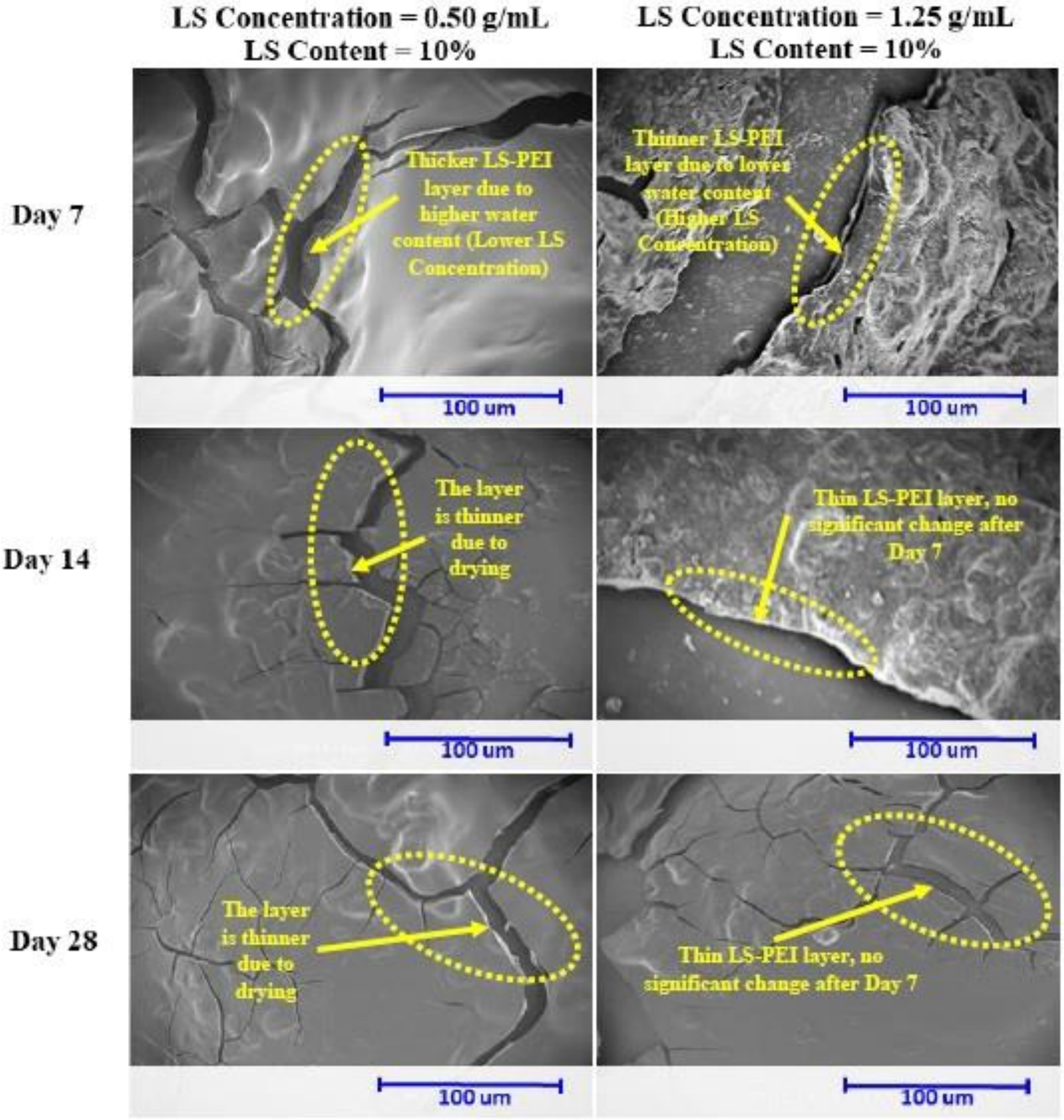


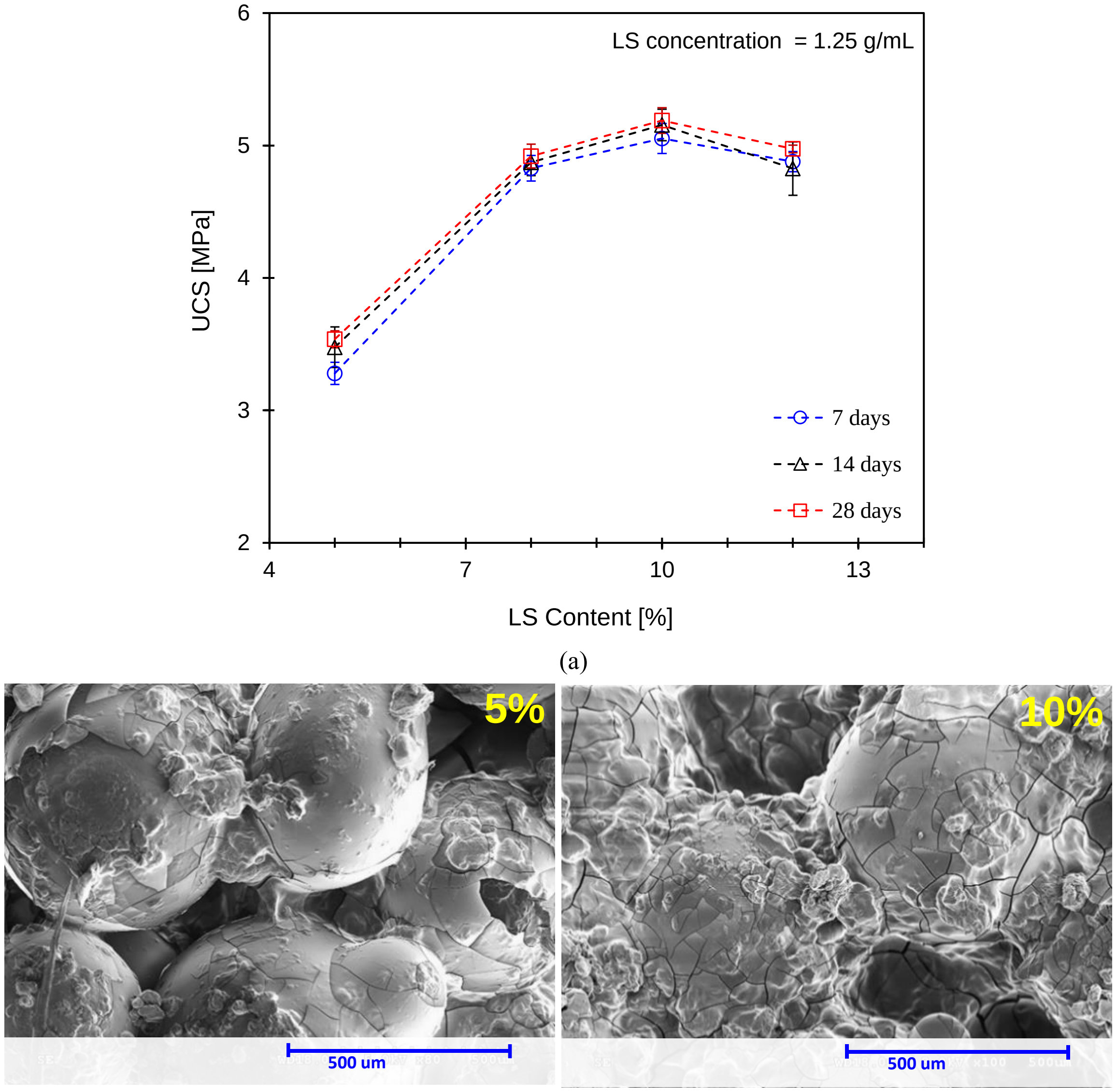
Fig. 5 SEM images of tested materials according to curing time

UCS of the specimen when the LS content exceeds 10%. It may be a consequence of the reciprocal repulsive forces between the charged parts of the admixture due to the overabundant of LS chains required to bind the soil particles (Ta'negonbadi and Noorzad 2017, Zhang *et al*. 2016).

3.4 Shear behavior of LS-PEI treated soil

Fig. 7 presents the variation of pairs: deviatoric stress - axial strain and excess pore water pressure - axial strain in the triaxial consolidated-undrained at the confining stress (σ_c) of 100 kPa for untreated (i.e., LS=0%) and treated specimens.

The deviatoric stress demonstrates an increasing trend with higher LS content. For example, at a confining stress of 100 kPa, the deviatoric stress increases from 365 kPa at 5% LS content to 420 kPa at 10% LS content, reaching its maximum at this concentration. This trend aligns with the results observed in the UCS test and could be attributed to the increase in physical and chemical bonds between soil particles, facilitated by the higher LS content. Nevertheless, for specimens treated with more than 10% LS content, there may be a repulsive force due to the over-sufficient LS chains in the specimen, which leads to a slight drop in strength. From the change in excess pore water pressure (Δu), it could be suggested that the specimens have a dilative behavior due to the fluctuating value of Δu from positive to negative. The untreated specimen shows the largest $+\Delta u$ and the smallest $-\Delta u$, while for the LS treated specimen, the $+\Delta u$ is smaller compared to the untreated specimen, and the $-\Delta u$ increases with the increasing LS content. Similar trends were observed at different confining stress levels. Note that deviatoric stresses



(a)

(b)

Fig. 6 (a) the variation of UCS with LS content at different curing times and (b) SEM images for glass bead coated by lignosulfonate of 5% and 10%

for both untreated and treated specimens also increase with increase in the confining stress; and by increasing the confining stress, the +Δu levels increase, whereas the magnitude of -Δu decreases.

Fig. 8 shows the change in shear strength parameters such as cohesion (*c*) and internal friction angle (*Φ*) with varying LS contents. Both total and effective cohesions increase with increasing LS content due to binding and coating between the soil particles and the binder. On the other hand, the internal friction angle shows a slight decrease of ~1° or little change, resulting from the decrease in angularity of pure silica sand coated with the LS-PEI binder has a smoother surface. Note that previous studies showed that the failure envelope of cemented soil using cement, gypsum, or lime is almost parallel to that of uncemented soil (Choo *et al.* 2018, Lee *et al.* 2009), indicating that the increase in shear strength is mainly due to chemical bonding (i.e., cohesion) at interparticle contacts. Note that the pure LS treated sample (i.e., without PEI) could not be used to conduct the TX test according to the washing out of LS within the circulation and saturation of the tested specimen.

The normalized 50% secant elastic modulus (E_s) determined from the stress-strain curves of the untreated and treated specimens obtained from the triaxial test are summarized in Fig. 9(a). Although the elastic modulus of the treated sample shows a higher value than that of the untreated sample, it decreases with increasing LS content due to the physical characteristic of biopolymer gel, which has rubber-like behavior (Chen and Indraratna 2015a, b, Ta'negonbadi and Noorzad 2017). The failure mode of the soil depends on how the soil responds to the applied stress, such as in the brittle or ductile mode. According to Bishop (1971), the ductility or rigidity of the specimen could be assessed by the brittleness index (I_B), which is the ratio of the difference between the deviatoric stress at peak and at ultimate ($q_{peak} - q_{ultimate}$) to the

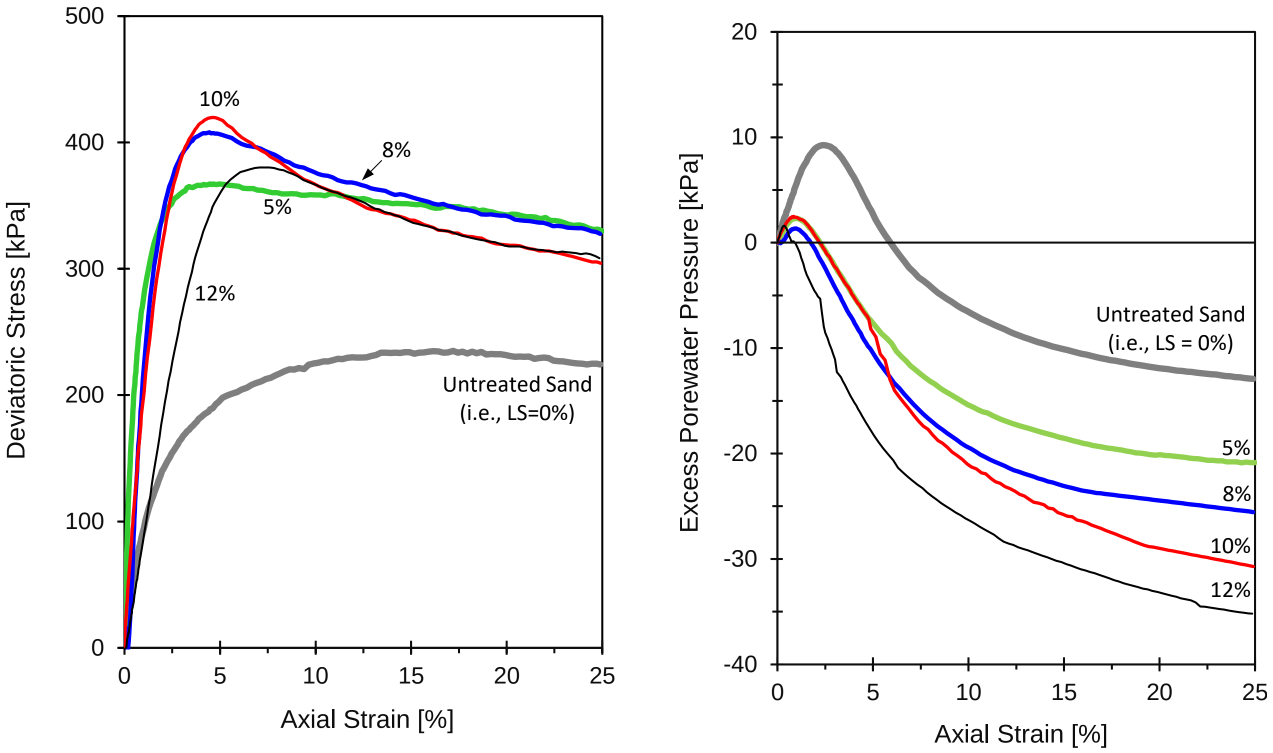


Fig. 7 Variation of deviatoric stress and excess pore water pressure (Δu) with axial strain of specimens at the confining stress (σ_c) of 100 kPa

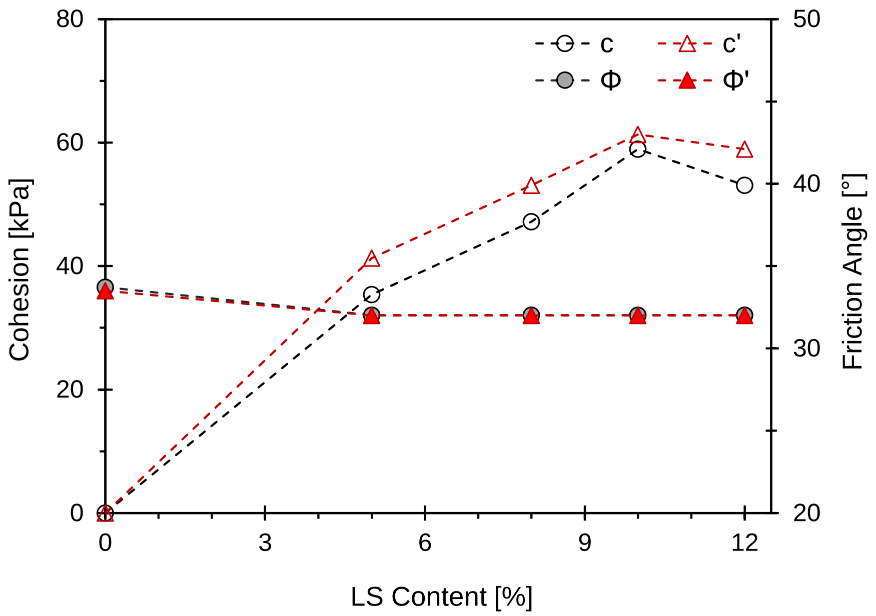
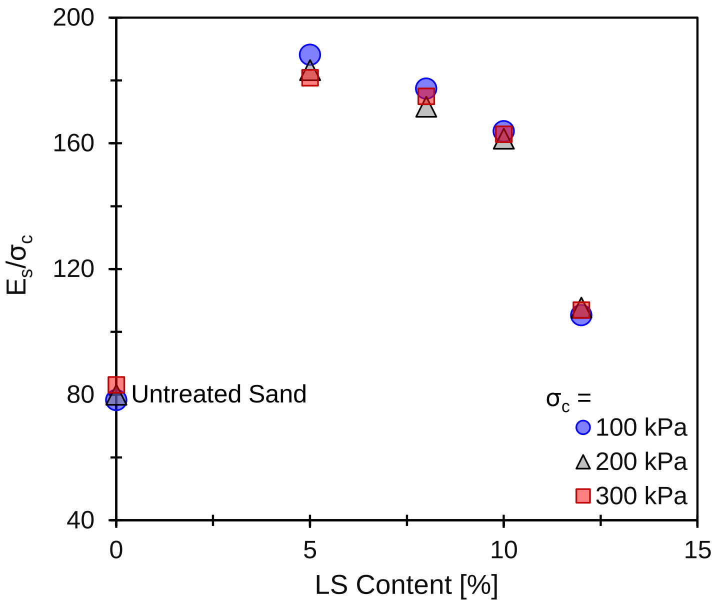
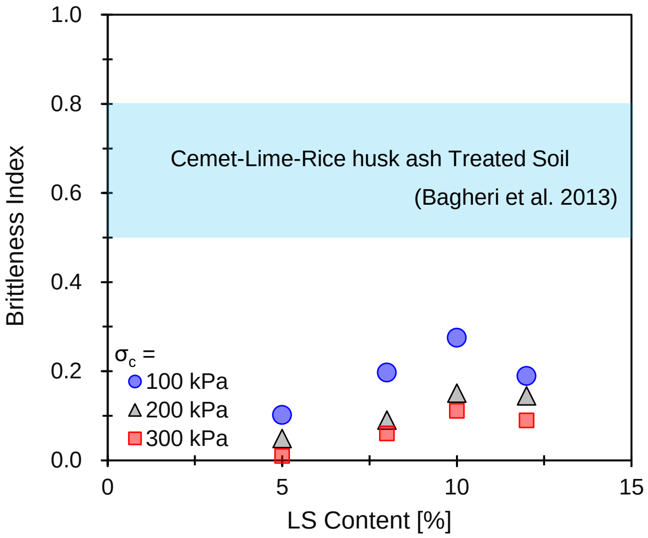


Fig. 8 Variations of cohesion and internal friction angle of tested materials according to LS content

peak deviatoric stress *(q_{peak})*; the lower the brittleness index, the higher the ductility. Fig. 9(b) indicates the brittleness index of samples treated with different LS contents. As shown in Fig. 9(b), the ductility of the specimen decreases with increasing LS content. However, soil treated with LS-PEI still behaves more ductile than some traditional stabilizers such as soil treated with cement-lime-rice husk ash (CLR), which was suggested by Bagheri *et al.* (2014), and which fails abruptly after reaching the peak value despite being treated with different stabilizer contents.



(a)



(b)

Fig. 9 The influence of LS-PEI binder on: (a) secant elastic modulus and (b) brittleness index

3.5 Water-resistant characteristic of LS-PEI treated soil

Fig. 10 illustrates the variations in UCS of the specimens treated with LS-PEI binder during the wetting-drying cycles. After 24 hours of soaking in the water tank, the compressive strength of the specimen rapidly drops from 5.05 MPa (initial UCS at dry state) to approximately 0.50 MPa (about 10% of initial UCS at dry state) due to the weakening of the intermolecular bonding, caused by the swelling via hydrophilic water absorption, which loosens bonding between the LS-PEI binder and sand particles. However, after being redried in the controlled room for seven days, the compressive strength of the specimen sharply recovers to 4.37 MPa (about 86.5% of initial UCS at dry state) due to the redevelopment of intermolecular bonding. Furthermore, at the end of the fourth cycle, it can be seen that both wet and dry compressive strengths remain almost constant at 0.48 MPa and 4.23 MPa, respectively. Therefore, the resistance to water has been improved since the specimen breaks down without PEI, and the LS leaches out because it touches the water surface. To provide a precise microstructure of the LS-PEI binder coating on the specimen within wetting and drying processes, the microstructures of the glass beads treated with LS-PEI binder were captured by SEM and are shown in Fig. 11. It can be seen in Figs. 11(c) and 11(d) that, in wet conditions, the thickness of the binder becomes thicker than its initial thickness, as shown in Figs. 11(a) and 11(b), and after redrying, Figs. 11(e) and 11(f) show that the thickness of the binder decreases to a value almost equal to its initial state and covers the surface again. Due to this phenomenon,

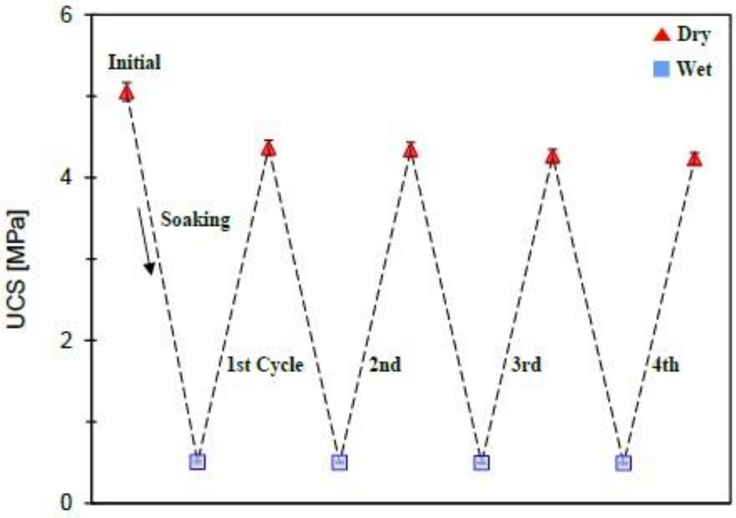


Fig. 10 UCS values of tested materials after wetting-drying cycles (LS content = 10% and LS concentration = 1.25 g/mL)

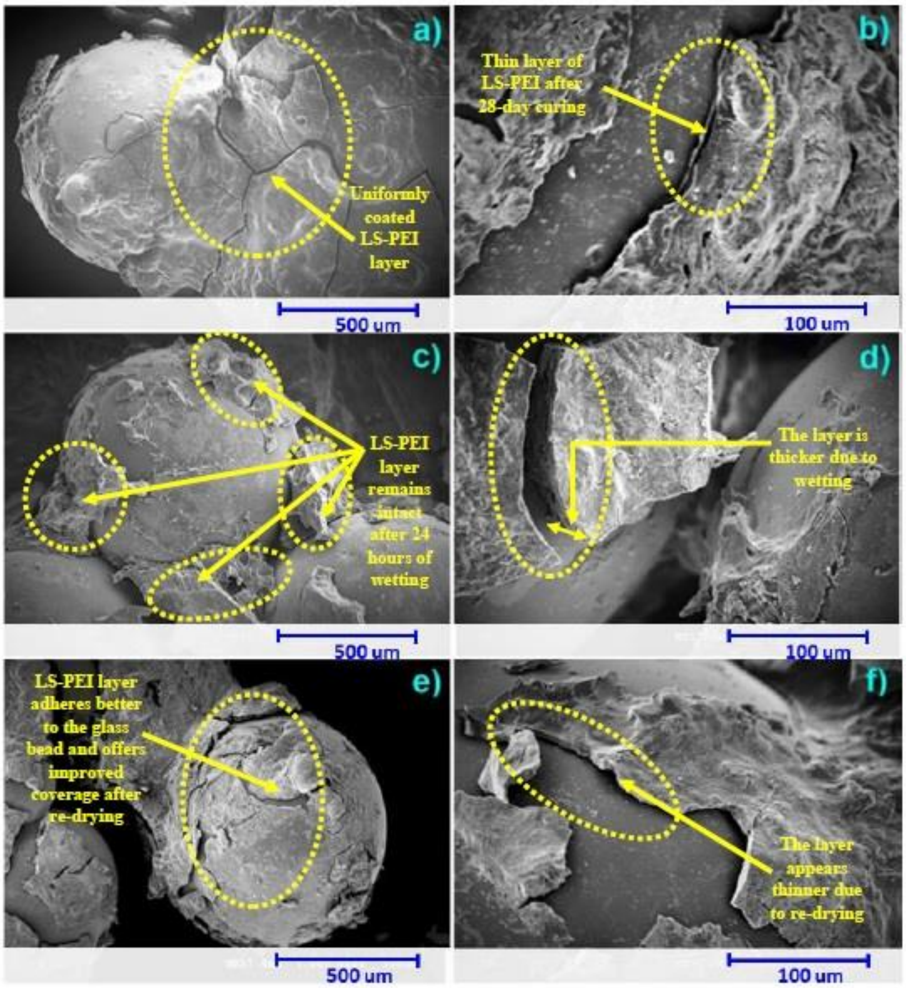


Fig. 11 Microstructure of glass bead coated by lignosulfonate-PEI binder: (a) & (b) initial state; (c) & (d) wet state; (e) &(f) re-drying state

the interaction between individual polymer molecules becomes stronger again, which ultimately results in an increase in the adhesion between the binder and the soil particles, as well as a significant increase in the compressive strength (Chen *et al.* 2019).

4. Conclusions

This experimental study aims at investigating the mechanical strength and water resistance of the granular soil treated by lignosulfonate-polyethyleneimine (LS-PEI). Various experiments such as unconfined compressive strength, triaxial, and cyclic wetting-drying tests were conducted to explore the engineering properties of LS-PEI treated sand with varying LS contents and concentrations. The results of this study demonstrate the followings:

1. The strength of LS-PEI treated soil sharply increases with increase in the amount of LS-PEI binder. Higher LS concentration and the longer curing time develop higher strength because the greater water dehydration from the specimen leads to having stronger interactive bonding between soil particles.
2. The LS-PEI treatment can enhance the stiffness of the soil. In addition, the LS-PEI treated sample reveals dilative behavior with high ductility characteristics.
3. After four cycles of wetting and drying, LS-PEI treated specimens do not show any disintegration into water. Although the UCS of the specimen in wet condition decreases to 10% of its UCS at the initial dry state, it recovers about 86% of its UCS after being redried. Moreover, the UCS value within four cycles at wet and dry states remains almost constant.
4. The results of this study suggest that the LS-PEI treatment for the granular soils can be applied as an environment-friendly alternative method for soil stabilization compared with the conventional methods

Overall, this research offers valuable insights into the potential of LS-PEI for soil stabilization in transportation infrastructure and geotechnical engineering applications. However, further investigation is necessary to evaluate its long-term performance and sustainability across various soil types. Additionally, to achieve improved engineering strength, exploring other additives alongside LS-PEI may be beneficial. Field implementation is also crucial to bridge the gap between laboratory findings and real-world applications, ensuring a comprehensive assessment of LS-PEI's effectiveness and feasibility in transportation infrastructure projects.

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