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Shear behaviour of a lignosulfonate treated silty sand

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ABSTRACT

Chemical treatment is a widely accepted cost effective ground improvement technique for stabilising problematic soils. However, the traditional soil stabilisers (e.g. cement and lime) are not always readily acceptable in Australia due to stringent occupational health and safety issues. They have been identified to cause serious environmental problems by altering the pH of soil and groundwater upon treatment. Moreover, excessive use of traditional admixtures to stabilize soil would also affect the yielding capacity of soils. To overcome these consequences, an alternative soil stabiliser that improves the properties of soil without causing adverse effect on the environment must be found. In this context, lignosulfonate has proved its effectiveness in stabilising erodible and dispersive soils and thereby reducing soil erosion. However, currently there are no comprehensive studies carried out to understand the shear behaviour of lignosulfonate-treated soils. In this study, a series of direct shear tests was conducted on a highly erodible silty sand to understand the shear and volume change behaviour of lignosulfonate-treated soil. The laboratory shear tests indicated that the peak and ultimate shear strength, as well as the angle of internal friction increased with the increasing amount of lignosulfonate. The volume change behaviour showed a dilative response after the lignosulfonate treatment and the change in ductility due to lignosulfonate treatment was negligible. In this respect, the lignosulfonate-treated soils would have an advantage over conventional chemical treatment methods, especially for cyclic loading such as fast moving traffic and high-speed rail.

Keywords: Chemical stabilisation, Lignosulfonate, Shear behaviour, Direct shear test, Silty sand

1 INTRODUCTION

In the recent past, a number of studies have been carried out on the behaviour of chemically stabilised soils including the mechanical properties such as peak and residual/ultimate strength, stiffness, brittleness, cohesion, peak and residual/ultimate friction angle. All these studies were carried out on the traditional admixture such as cement, lime gypsum, fly ash. It has been reported that with the increasing amount of cement, the peak shear strength, cohesion and the stiffness have been increased while the residual/ultimate shear strength has not been affected by the cementation (e.g. Abdulla and Kiousis 1997; Consoli et al. 1998; Schnaid et al 2001; Wang and Leung 2008). Haeri et al (2006) studied the behaviour of a lime treated gravelly sand and observed that the peak strength, cohesion intercept, stiffness and brittleness increase while the volume change becomes more dilative with the increasing amount of lime.

Despite the fact that these traditional chemical stabilisers can enhance the soil properties, they are not always readily acceptable due to environmental problems upon treatment. Chemical additives such as cement and lime change the pH value of soil after treatment (Little 1995; West and Carder 1999; Rollings et al. 1999; Hassan et al. 2008; Kitazume and Terashi 2013) which affects the quality of ground water and limits the scope of the vegetation. Changes of soil pH upon treatment also affect the longevity of steel frame structures on the ground (Perry 1977; Biggs and Mahony 2004). Moreover, cementitious chemical admixtures reduce the soil fertility (e.g. Jaynes et al. 1995; Kitchen and Sudduth 1996) and decrease the soil chemical aspects such as cation exhchange capacity and the electrical conductivity (e.g. Boardman et al. 2001; Chen et al. 2009). Increased brittleness of soil due to chemical treatment (Sariosseiri and Muhunthan 2009) reduces the yielding capacity of soil which affects the stability of structures. To overcome these problems caused by traditional admixtures, an environmentally friendly alternative soil stabiliser must be found. In this circumstance, lignosulfonate has been experimentally proven to be effective in stabilising some problematic soils (Pengelly et al.

1997; Puppala and Hanchanloet 1999; Tingle and Santori 2003; Indraratna et al. 2008a, b; Vinod et al. 2010; Indraratna et al. 2013). Lignosulfonate is a by-product of wood processing industry which can be obtained in liquid form. It is non-toxic, non-flammable and completely soluble in water. Lignosulfonate has a specific gravity of 1.2 and its pH value is 3.8 (Muttuvel 2008). A study by Indraratna et al. (2008a, b) revealed that lignosulfonate can enhance the erosion resistance of highly erodible and dispersive soils, and thereby reduce the rate of soil erosion significantly. The effect of lignosulfonate on the compressive strength of kaolin clay and a clay mixture (95% kaolin and 5% montmorillonite) was reported by Vinod et al. (2010) and Indraratna et al. (2012) using standard Unconfined Compressive Strength (UCS) tests. They observed that the ultimate strength and stiffness increase with the increased amount of lignosulfonate. Also, they reported that the modulus (E/q_u, where E is the secant young's modulus and q_u is the ultimate strength) increased with the increasing amount of lignosulfonate, with no change in the failure strain. However, currently there are no in-depth studies carried out to understand the stress-strain behaviour of lignosulfonate treated soils. Therefore, in this study, a series of direct shear tests were carried out to understand the shear behaviour of a lignosulfonate treated silty sand.

2 EXPERIMENTAL INVESTIGATION

2.1 Sample preparation and test procedure

A highly erodible soil collected from Wombayen Caves, Australia was used in this study to investigate the shear behaviour of lignosulfonate treated soil. This particular soil was classified as a silty sand (SM) according to the Unified Soil Classification System. The particle size distribution curve of the selected soil is shown in Figure 1. Other soil properties and the properties of lignosulfonate used are given in Table 1.

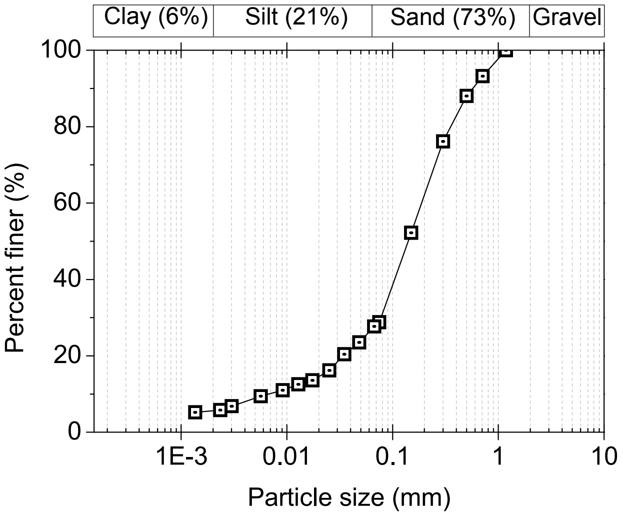


Figure 1. Particle size distribution of the silty sand used in this study (After Indraratna et al. 2013)

Table 1: Properties of materials used in this study (After Athukorala et al 2013)

Silty sand		Lignosulfonate	
Property	Value	Property	Value
G_s	2.67	G_s	1.2 approx.
OMC & MDD	11.6% & 18.03 kN/m^3	pH value	3.8 approx.
Liquid limit	22.5	Appearance	Dark brown liquid
Plasticity index	Non-plastic	Solubility in water	Completely soluble
Erodibility (AS1289.3.8.3 - 1997)	D1	Other properties	Non-flammable Non-toxic

A compaction level of 95% Maximum Dry Density (MDD) was selected for preparing the specimens for the shear tests. Muttuvel (2008) has observed that the effect of lignosulfonate on Optimum Moisture Content (OMC) and MDD is negligible for Wombeyan caves silty sand. Therefore, it was assumed that the values of OMC and MDD for both lignosulfonate treated and untreated soils are same. To maintain this density in every specimen, a specially designed mould was made so that the soil sample could be compacted to achieve the required dry density. This mould consists of a top plate, a casing, and a bottom plate. The mould is designed in such a way that when the soil sample is fully compacted, the specimen reaches the standard size (60mm×60mm×25mm) required to test in the shear box apparatus.

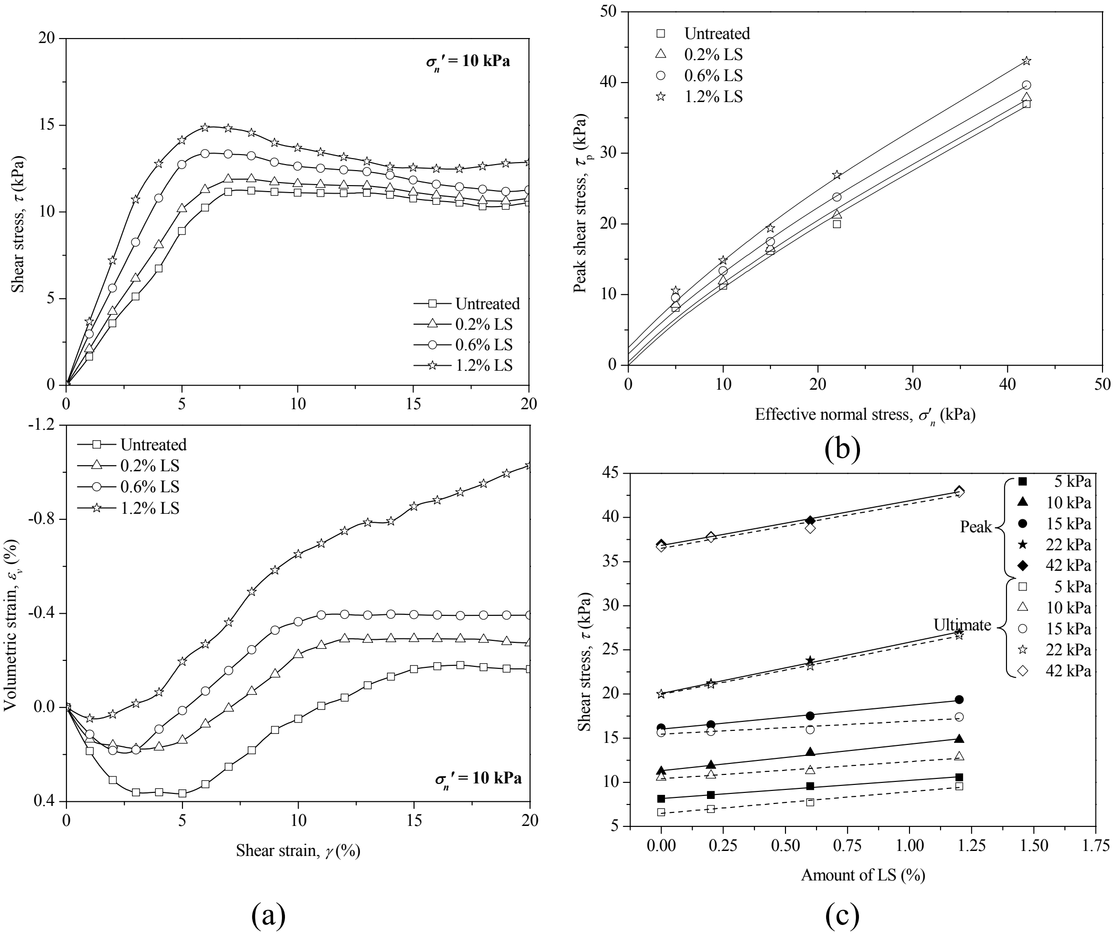
The treated soil samples were prepared by adding the predetermined amount of lignosulfonate (0.2%, 0.6% or 1.2% by dry soil weight) and water to dry soil. This mixture was placed in layers inside the casing assembled with the bottom plate, with each layer being flattened softly with a wooden tamp. After filling all the amount of mixed soil into the mould, the top plate was placed in position and the mould was subjected to a uniform pressure using the compression machine until the top plate touches the mould. The compacted specimen was then pushed out of the mould carefully with the wooden tamp and wrapped in moisture-proof bags before being kept in a temperature controlled room for curing.

After curing for 7 days, the specimen was pushed carefully into the shear box using the wooden tamp and then saturated with water for 24 hours. Each specimen was then subjected to consolidated drained direct shear testing under a constant shearing rate of 0.05mm/min. This shearing rate was determined according to ASTM D3080 (2004) such that there is no excess pore pressure development during shearing. The normal stresses used in this study were 5 kPa, 10 kPa, 15 kPa, 22kPa, and 42 kPa.

3 RESULTS AND DISCUSSION

3.1 Stress-strain characteristics and volumetric behaviour

The observed variations of shear stresses (τ) and the volumetric strains (ε_v) with the shear strain (γ) of lignosulfonate treated and untreated silty sand at 10kPa effective normal stress are presented in Figure 2(a). All the tests were carried out up to a shear strain of 20%. It is evident from Figure 2(a) that the lignosulfonate has significant influence on the shear stress and volumetric strain behaviour of silty sand. The shear stress increases and the volumetric strain response exhibits a dilative behaviour with increase in the percentage of lignosulfonate. The failure envelopes of the lignosulfonate treated and untreated silty sand corresponding to peak shear strengths are shown in Figures 2(b). It is evident from Figures 2(b) that the shear strength and the apparent cohesion intercept are increased due to lignosulfonate treatment. These increments are attributed to the chemical bonding between soil particles formed by lignosulfonate treatment (Vinod et al. 2010). As expected, the lignosulfonate treated soil exhibits a low apparent cohesion compared to the soil treated with traditional admixtures. In order to understand the improvement in the shear strength of the silty sand due to lignosulfonate treatment, the peak and ultimate shear strengths are plotted against the amount of lignosulfonate, and shown in Figures 2(c). The post-peak or ultimate shear strengths were determined from the stress-strain curves at 20% shear strain where the shear stress reaches constant value after the peak. The scattered points in Figures 2(c) represent the experimental strengths shown in the failure envelopes and the line graphs represent linear approximations. Figures 2(c) indicates that both the peak and ultimate strengths increase linearly with the increasing amount of lignosulfonate.



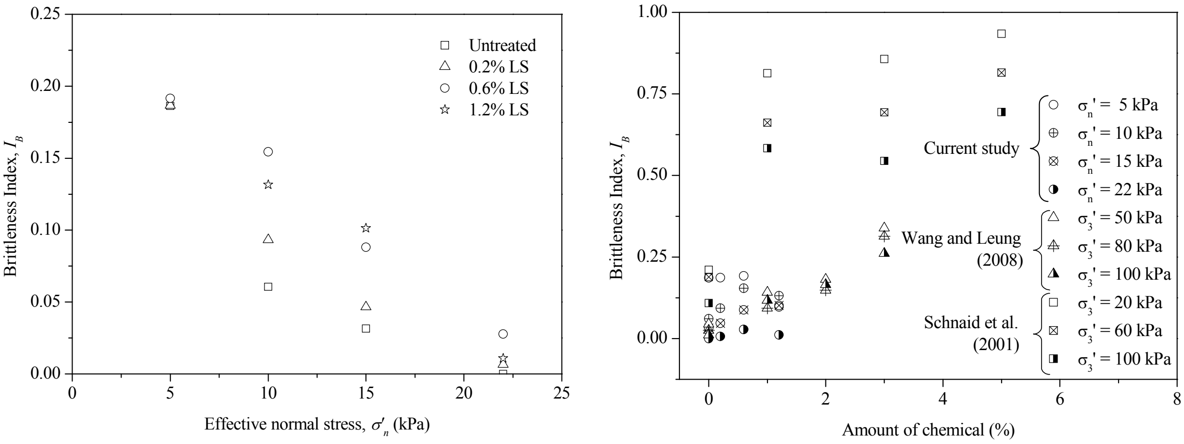
(a) (b) (c)

Figure 2. (a)Variations of shear stresses and volumetric strains of lignosulfonate treated and untreated silty sand with shear strain under effective normal stress of 10kPa (b) peak failure envelopes (c) Variation of peak and ultimate shear strengths with the amount of lignosulfonate
(After Athukorala 2013)

In order to study the effect of lignosulfonate treatment on the stress-strain characteristics, the brittleness index (I_B) was considered as a measure of ductility. I_B was first introduced by Bishop (1971) and defined as:

$$I_B = \frac{(\tau_p - \tau_r)}{\tau_p} \qquad (1)$$

where, τ_p is the shear stress at peak and τ_r is the residual strength. The brittleness indices for lignosulfonate treated and untreated silty sand were calculated from the direct shear test results directly using Equation (1). The variation of brittleness index with the effective normal stress is shown in Figure 3(a) which shows that the brittleness index decreases with increasing effective normal stress for both lignosulfonate treated and untreated soil. In other words, the silty sand becomes more ductile with the increased effective normal stress. However, the change of brittleness due to lignosulfonate treatment appears to be insignificant compared to the soil treated with cement (Figure 3(b)). In Figure 3(b), the brittleness indices of lignosulfonate treated silty sand are compared with those of two cement treated sands from triaxial testing reported by Wang and Leung (2008) and Schnaid et al (2001). Wang and Leung (2008) and Schnaid (2001) reported the drained triaxial compression test results of cement treated soil for different confining pressures (e.g. 20kPa, 60kPa, 80kPa and 100kPa).



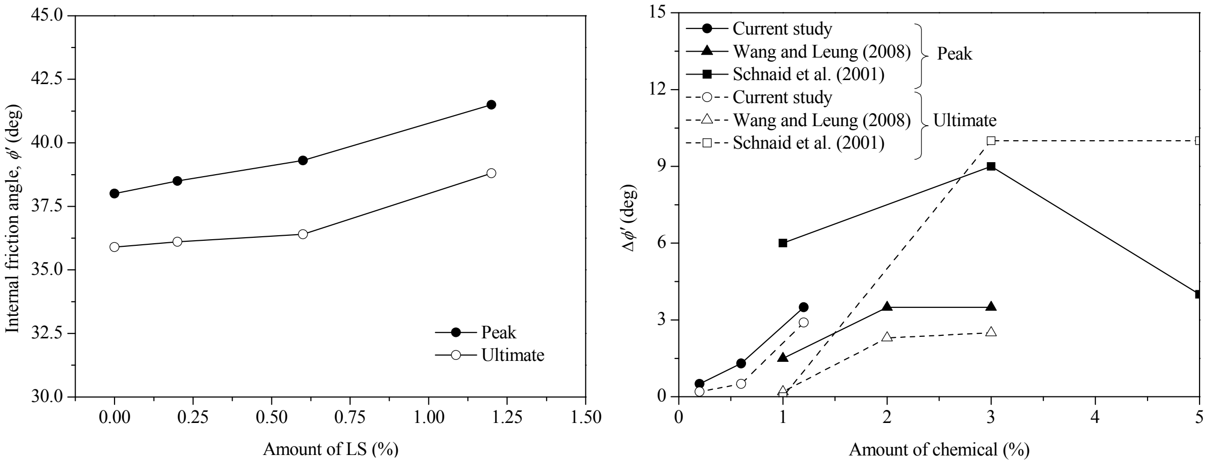
(a) (b)

Figure 3. (a) Variation of brittleness index with the effective normal stress for lignosulfonate treated and untreated silty sand (b) Comparison of brittleness indices of lignosulfonate treated silty sand with those of cement treated sands (After Athukorala 2013)

It is evident from the Figure 3(b) that even under a very low effective normal stress, such as 22 kPa, the increase in the brittleness index of the silty sand due to lignosulfonate treatment is not significant. When the confining pressure (or effective normal stress) is increased, the brittleness should decrease, i.e., the soil becomes more ductile. In other words, under low effective normal stresses, soil specimens should show high brittleness indices. Therefore, one can expect no brittleness index increments due to lignosulfonate treatment at higher effective normal stresses.

3.2 Effect of lignosulfonate treatment on the internal friction angle

The variations of the peak and ultimate friction angles with the amount of lignosulfonate are illustrated in Figure 4(a). It can be observed from Figure 4(a) that the peak and ultimate friction angle increases with the increase of LS. As expected, peak friction angle exhibit a higher value compared to the friction angle at ultimate state. The angle of internal friction (ϕ') which can be taken as the slope of the failure envelope did not appear to be influenced significantly by the lignosulfonate treatment up to 0.6% lignosulfonate for both peak and ultimate conditions. The peak friction angle increases from 38° for untreated soil to 41.5° for soil treated with 1.2% lignosulfonate. The ultimate friction angle has increased from 36° to 39° after the treatment with 1.2% lignosulfonate.



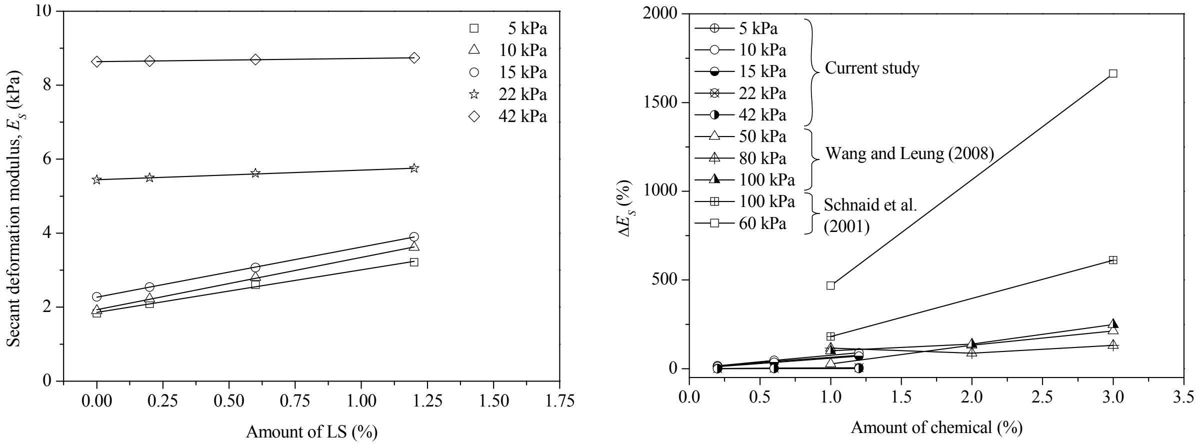
(a) (b)

Figure 4. (a)The change of the internal friction angle of silty sand with the amount of lignosulfonate (b) Comparison of change in internal friction angle due to lignosulfonate and cement treatments at peak and ultimate states (After Athukorala 2013)

The changes of peak friction angle ($\Delta\phi'_p$) and ultimate friction angle ($\Delta\phi'_u$) due to chemical treatment were calculated for sands treated with lignosulfonate and cement (Wang and Leung 2008; Schnaid et al. 2001) and presented in Fig.4. It is to be noted that the amounts of lignosulfonate used in the current study are very low compared to those of cement, and therefore the comparison on change in friction angles is limited only to 1-1.2% of chemical treatments. It is evident from Figure 4(b) that the change in peak friction angle due to 1.2% lignosulfonate treatment on dense silty sand is about twice of that of loose Ottawa sand treated with 1% cement. However, dense silty sand stabilized with 1% cement shows higher increments ($\Delta\phi'_p$) in peak friction angle than that of 1.2% lignosulfonate treated silty sand. When the ultimate friction angle is considered, neither loose sand nor dense sand shows increments in ultimate friction angle ($\Delta\phi'_u = 0$) for 1% cement treatment. Therefore, it can be concluded from Figure 4(b) that lignosulfonate is very effective in enhancing the ultimate friction angle for low chemical percentages (e.g <1.2%).

3.3 Effect of Lignosulfonate Treatment on Deformation Modulus

The observed variation of the secant deformation modulus ($E_S = \tau/\gamma$) of lignosulfonate treated and untreated silty sand is plotted with the amount of lignosulfonate and shown in Figure 5(a). In Figure 5(a), the secant deformation moduli of silty sand were approximated to vary linearly with the amount of lignosulfonate under different effective normal stresses.



(a) (b)

Figure 5. (a) Variation of secant deformation modulus with the amount of LS (b) Comparison of improvement in secant deformation modulus due to LS and cement treatments on sands (After Athukorala 2013)

Figure 5(b) compares the increased secant deformation modulus (ΔE_S) of lignosulfonate treated silty sand with that of sands treated with cement (Wang and Leung 2008; Schnaid et al. 2001). Since the deformation modulus depends highly on the effective normal stress, ΔE_S was calculated as a percentage of corresponding E_S of the untreated specimen for the purpose of comparison. The value of ΔE_S was determined using Equation (2) where E^t_S is the secant deformation modulus of the treated specimen and E^{ut}_S is that of untreated specimen corresponding to the same effective normal stress.

$$\Delta E_S = \frac{(E_S^t - E_S^{ut})}{E_S^{ut}} \times 100\% \tag{1}$$

Figure 5(b) illustrates that with the increased amount of lignosulfonate, ΔE_S is increased slightly under effective normal stresses of 5 – 15 kPa, but under 22 kPa and 42 kPa, there is no considerable increase in E_S. When considering the Ottawa sand treated with 1% cement at loose state (Wang and Leung 2008), the increments in secant deformation modulus are in the same range (0 – 100 %) as those of 1.2% lignosulfonate treated soil. The silty sand treated with 1% cement at dense state (Schnaid et al. 2001) shows higher increments (180 – 450%) in E_S. Therefore, it can be concluded from Figure 5(b) that the secant deformation modulus is not affected significantly by the lignosulfonate treatment when compared with the cement treated sands.

4 CONCLUSION

This study has presented the results of a series of direct shear tests carried out to understand the shear and volume change behaviour of a lignosulfonate treated silty sand. The test results revealed that with the lignosulfonate treatment, the peak shear stress and the dilation increases. As the level of lignosulfonate treatment increases, the brittleness index decreased for all the effective normal stresses considered. However, lignosulfonate does not change the ductility of soil significantly, compared to cement. The angle of internal friction increased with the increasing amount of lignosulfonate for both peak and ultimate states. The enhancement in the peak friction angle caused by 1.2% of lignosulfonate was less than that of 1% cement treated silty sand. However, lignosulfonate was found to be more effective than cement in enhancing the ultimate friction angle for low percentage of chemical. Enhancements of the secant deformation modulus (E_s), due to lignosulfonate treatment were more pronounced at lower effective normal stresses (5kPa, 10kPa and 15kPa) than at relatively higher effective normal stresses (22kPa and 42 kPa). However, the values of E_s increased linearly with the increasing percentage of lignosulfonate in the range of effective normal stresses considered in this study. Therefore, it can be concluded from this study that lignosulfonate can be used as an environmentally friendly alternative chemical admixture, for stabilising silty sand maintaining the original ductility and elasticity of the soil.

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