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ABSTRACT: This paper presents internal erosion behaviour of an erodible soil stabilized by chemical admixtures using a novel Process Simulation Apparatus for Internal Crack Erosion (PSAICE), designed and built at University of Wollongong. Laboratory tests were carried out on typical erodible soils (collected from Wombeyan caves, Australia) stabilised using chemical admixtures such as lignosulfonate and cement. Test results reveal that the erosion parameters such as critical shear stress and coefficient of soil erosion were improved with the increase in the amount of chemicals. It has been seen that lignosulfonate exhibits better performance in stabilizing the erodible soil compared to cement. Based on the observed erosion test results, an analytical model has been developed considering the tensile behavior based on the law of conservation of energy. Moreover, the stabilization mechanism of lignosulfonate treated soil has been developed using chemical analysis such as X-ray Diffraction (XRD) and Fourier Transform Infrared (FTIR) Spectroscopy studies.

1 INTRODUCTION

Highly erodible soils are common in many parts of the world. In recent years, chemical admixtures such as cement, lime, fly ash shows promising aspects in stabilising erodible soil. These chemical stabilisers generally alter the mineralogy of soil resulting in highly stable soil substances having improved inherent properties such as strength and stiffness. Numerous studies were conducted so far to investigate the applicability of traditional stabilisers on problematic soils such as soft clay and erodible soils (e.g. Balasubramaniam *et al.*, 1989; Indraratna *et al.*, 1995; Rajasekaran *et al.*, 1997; Uddin *et al.*, 1997; Chew *et al.*, 2004). However, such traditional admixtures (i.e. cement, lime, fly ash etc.) are not frequently useable because of stringent occupational health and safety issues apart from various threats to the environment due to envitable increase in soil and ground water alkalinity. Moreover, traditionally stabilised soil has a pH of 9 (Rollings *et al.*, 1999), which often affects the longevity of reinforcement of concrete and steel frame structures (e.g. Biggs and Mahony, 2004; Perry, 1977). In addition, other chemical aspects such as electrical conductivity and cation exchange capacity of soil decreases with the increasing amount of admixtures and curing time (e.g. Chen *et al.* 2009; Boardman *et al.*, 2001) that affect the water holding capacity as well as nutrients carrying capacity of soil resulting in lowering fertility (e.g. Lund *et al.*, 1999; Kitchen and Sudduth, 1996; Jaynes *et al.*, 1995). Thus, the excess use of traditional admixtures in soil

stabilisation could be harmful for the yielding capacity of soils (e.g. Nalbantoglu and Tuncer, 2001). On the other hand, the traditionally treated soil exhibits excessive brittle performance (e.g. Sariosseiri and Muhunthan, 2009) that affects the stability of structures, especially during cyclic and impact loading condition such as high speed rail and aircraft runways. To overcome above consequences, it is necessary to find out an alternative soil stabiliser, which could provide sustainable soil improvement without harming the environment. In the recent past, lignin based chemical, lignosulfonate has shown promising aspects in stabilising the problematic soils (Puppala and Hanchanloet, 1999; Pengelly et al., 1997; Tingle and Santori, 2003; Indraratna et al., 2008). Pengelly et al. (1997) carried out studies on expansive soils by injecting a chemical mixture consisting of ammonium lignosulfonate and potassium chloride and observed a significant reduction in swelling potential. In addition, a number of research studies have been conducted on low volume road construction to investigate the performance of lignosulfonate for improving the strength behaviour of sub-grade and also for effective control of dust emission (e.g. Chemstab, 2003; Tingle and Santori, 2003; Lohnes and Coree, 2002). Sherard et al. (1976) studied the erosion characteristics of soil by directing eroding fluid through a 1-mm crack (hole), i.e. standard pinhole test. Wan and Fell (2004) performed erosion tests by applying a hydraulic gradient across a 6 mm internal crack to study the erosion characteristics of unsaturated soil in cracks of embankment dams. Recently, Indraratna et al. (2008) conducted research on internal erosion behaviour of lignosulfonate treated dispersive soils using a novel Process Simulation Apparatus for Internal Crack Erosion (PSAICE). They concluded that lignosulfonate treatment improves the erosion resistance of the treated soil similar to traditional admixtures such as lime and cement. Therefore, the main focus of the current studies is to investigate the effectiveness of lignosulfonate in the stabilisation of erodible soil, and to develop an analytical model to capture the erosion behaviour of chemically treated erodible soil.

2 EXPERIMENTAL PROGRAM

2.1 Soil and chemicals used in the study

The erodible soil (e.g. silty sand) used in internal crack erosion tests was collected from Wombeyan caves, New South Wales (NSW), Australia. The soil contains about 50% sand, 44% silt, and 6% clay. According to the standard pinhole test (ASTM D 4647), the erodible soil can be classified as D1 type dispersive soil. The maximum dry density and optimum moisture content for erodible soil were observed to be 1711 kg/m^3 and 10.3%, respectively.

For this study, general purpose Portland cement and lignosulfonate were selected as admixtures. The lignosulfonate is a completely soluble, dark brown liquid having a pH value of approximately 4. It is characterised as inflammable, non-corrosive and non-hazardous chemical according to the National Occupational Health and Safety Commission (NOHSC) criteria (Chemstab, 2003).

2.2 Internal crack erosion test

Internal crack erosion studies were conducted using the Process Simulation Apparatus for Internal Crack Erosion (PSAICE) shown in Figure 1. Detailed explanation of testing equations and testing procedure can be found elsewhere (e.g. Indraratna et al. 2008). The erosion behaviour of treated and untreated soils have been examined in terms of erosion rate and hydraulic shear stress to calculate the erosion parameters, namely, the critical shear stress and the coefficient of soil erosion. The critical shear stress, τ_c is defined as the minimum hydraulic shear stress required to initiate erosion. Figure 2 shows the variation of the erosion rate with the hydraulic shear stress. The critical shear stress was calculated by extrapolating the straight line to the X-axis, and the slope of the linear line represents the coefficient of soil erosion. Figure 3 shows the typical plot of effluent turbidity and flow rate with time. It was observed that the turbidity increased initially, and then decreased as erosion occurred (Fig. 3). However, the flow rate was observed to increase steadily

with time. The value of k was then evaluated from the linear relationship between the soil concentration and the turbidity (Figure 4). The value of k was found to be 0.013 kg/m³/NTU for cement treated and untreated erodible soil and 0.011 kg/m³/NTU for lignosulfonate treated soil. In addition, when the diameter of the soil crack changes by $\delta\phi$ in a time interval δt, the erosion rate,

$\dot{\varepsilon}$ (kg/s/m²), can then be calculated using Equation (1)

$$\dot{\varepsilon} = \frac{kQT}{\pi\phi_i l} \qquad (1)$$

where, k is an empirical factor relating the turbidity of eroded fluid; Q is the average flow rate through the soil pipe at time interval δt in m³/s; T is the average turbidity of effluent at δt in NTU; and l is the length of soil pipe in m.
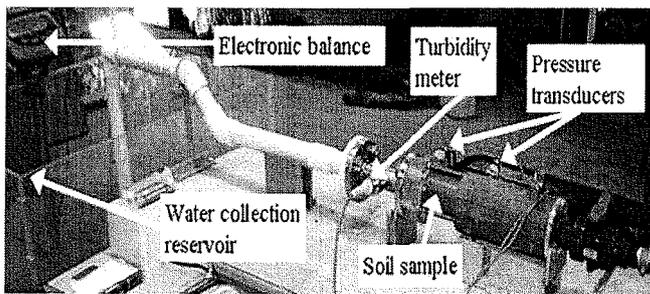
Figure 1. Photograph of Process Simulation Apparatus (Indraratna *et al.*, 2008)
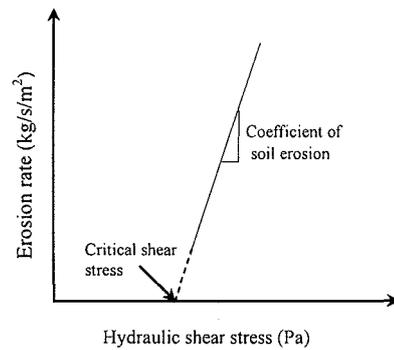
Figure 2. Typical plot of erosion rate versus hydraulic shear stress (Indraratna *et al.*, 2008)
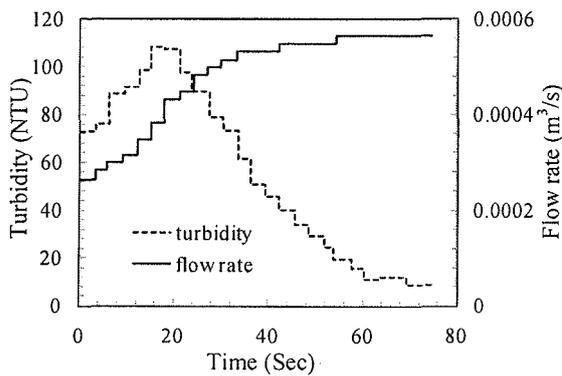
Figure 3. Typical plot of turbidity and flow rate with time for the erodible soil (Indraratna *et al.*, 2008)
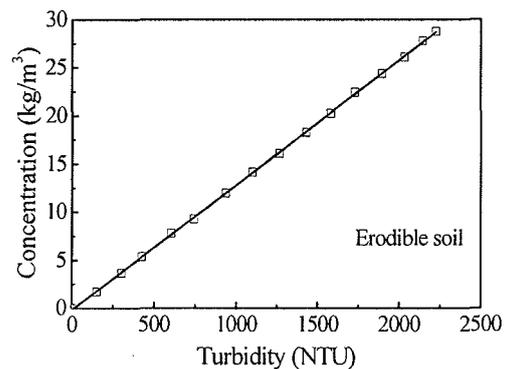
Figure 4. Relation of soil concentration with turbidity for the erodible soil (Indraratna *et al.*, 2008)

Hydraulic Shear Stress from Friction Factor Method
The hydraulic shear stress can be estimated from:

$$\tau_a = \frac{f\rho_w v^2}{8} \qquad (2)$$

where, f is the friction factor, ρ_w (kg/m³) is the density of the eroding fluid; and v (m/s) is the mean velocity of the flow through the crack at time t. The friction factor was calculated from the

Moody diagram (Abulnaga, 2002) based on the relative roughness and the Reynolds number. The relative roughness can be calculated by the following equation:

$$\varepsilon = \frac{D}{2\phi_t} \tag{3}$$

where, D (m) is the mean particle diameter, ϕ_t (m) is the diameter of soil pipe at time t.

The Reynolds number can be calculated using Equation (4):

$$R_e = \frac{\rho_w v \phi_t}{\mu} \tag{4}$$

Where, μ (kgm^{-1}s^{-1}) is the dynamic viscosity of the eroding fluid

2.3 Internal Erosion test result

The variation of erosion rate with the hydraulic shear stress for lignosulfonate treated and untreated erodible soil is presented in Figure 5. It is evident that the erosion rate and hydraulic shear stress follow a linear relationship, and the slope represents the coefficient of soil erosion. It is observed that the critical shear stress increases and the coefficient of soil erosion decreases with the increase of lignosulfonate. When the amount of lignosulfonate is increased to 0.6 %, the critical shear stress increases from 0.8 Pa to 35 Pa. In addition, the coefficient of soil erosion decreases from 0.265 sm^{-1} to 0.003 sm^{-1} (Fig. 5). On the other hand, the critical shear stress increases from 0.8 Pa to 43.4 Pa and the coefficient of soil erosion decreases from 0.265 sm^{-1} to 0.002 sm^{-1} due to the addition of 3% cement (Fig. 6). It is clear from the above investigation that lignosulfonate performs better than cement in improving the erosion resistance of erodible soil.
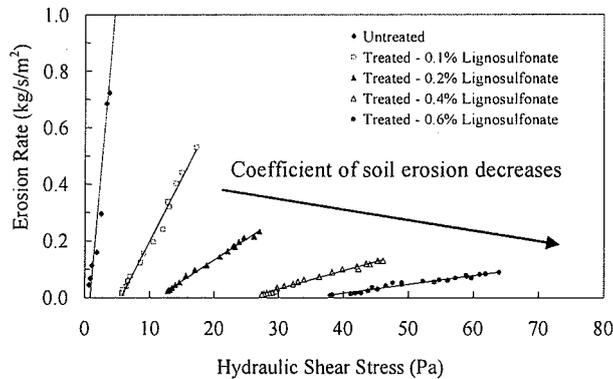

Figure 5. Erosion rate against hydraulic shear stress for lignosulfonate treated and untreated erodible soil (Indraratna et al., 2009)
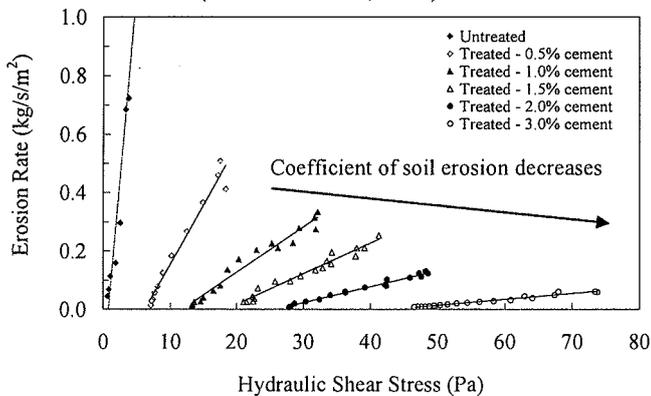

Figure 6. Erosion rate against hydraulic shear stress for cement treated and untreated erodible soil (Indraratna et al., 2009)

3 THEORETICAL PREDICTIONS

An analytical model has been developed to simulate the erosion of soil capturing its tensile behaviours based on the law of conservation of energy. This model captures the erosion of soil by following two steps including (a) the detachment of particles by the eroding fluid resulting in suspended load, and (b) transportation of suspended load. Therefore, the energy required to complete the erosion process is the sum of energy consumed for the detachment of soil particles and for their transportation. According to the law of conservation of energy, the sum of energy used for detachment and transportation should be equal to the energy dissipated by water during erosion.

Energy dissipated by water during erosion
During erosion, excess hydraulic shear stress performs work for the detachment and transportation of soil particles. The energy dissipated by the excess hydraulic shear stress ($\Delta E'$) within a time interval (δt) is equal to the product of the excess hydraulic shear force and the distance travelled, hence:

$$\Delta E' = \omega(\tau_a - \tau_c)\pi\phi_t lv\delta t \tag{5}$$

In equation (5), v is the mean flow velocity through soil pipe in m/s, l is the length of soil pipe in m, ϕ_t is the diameter of soil pipe in m, τ_a is the hydraulic shear stress in Pa, and τ_c is the critical shear stress in Pa, ω is the efficiency index, which needs to be determined experimentally.
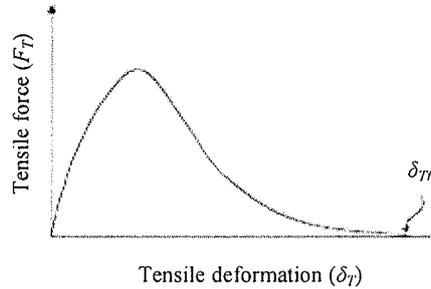

Figure 7. Typical tensile failure behaviour of soil (Indraratna *et al.*, 2009)

Energy dissipation by particle detachment
 The energy required to break the interparticle bonds on the fracture plane to achieve the tensile failure (E_T) can be defined by Figure 7, which can be expressed by Equation 6.

$$E_t = \int_0^{\delta_{Tf}} F_T d\delta_T \tag{6}$$

where, F_T is the tensile force in Newton, δ_{Tf} is the failure tensile deformation in m, and δ_T is the tensile deformation in m.

The total energy (ΔE_d) necessary for detaching interparticle bonds during erosion (in time interval δt) can be calculated by the following equation:

$$\Delta E_d = \frac{3}{Ad}\left(\frac{k'}{k}\right)(\pi\phi_t l\delta\phi_t)E_T \tag{7}$$

where, k and k' represent the mean coordination number and the average number of common contacts per particles, respectively.

Determination of energy used to transport particles
 The total energy used to transport all particles is equal to the kinetic energy gained and is given by:

$$\Delta E_t = \frac{v^2}{4}(\pi\phi_t l\delta\phi_t) \tag{8}$$

where, ΔE_t is the energy used to transport particles in J, and ρ_d is the dry density of the soil in kg/m^3.

Model Formulation

According to the law of the conservation of energy, the fraction of energy used for erosion is equal to the energy used for the detachment and transportation of particles. This yields an expression for the rate of change of soil pipe diameter as follows:

$$\frac{\delta \phi_t}{\delta t} = \frac{\omega(\tau_a - \tau_c)v}{\left[\dfrac{3}{Ad}\left(\dfrac{k'}{k}\right)E_T + \dfrac{v^2}{2}\rho_d\right]} \qquad (9)$$

The equation of the erosion rate then can be simplified as

$$\varepsilon = \frac{\omega(\tau_a - \tau_c)v\rho_d}{\left[\dfrac{3}{Ad}E_T + \dfrac{v^2}{2}\rho_d\right]} \qquad (10)$$

where ε is the erosion rate in kg/s/m^2, ω is the efficiency index, τ_a is the hydraulic shear stress in Pa, τ_c is the critical shear stress in Pa; v is the mean flow velocity in m/s, E_T is the energy required to break a number of interparticle bonds in the fracture plane in J, ρ_d is the dry density of the soil in kg/m^3, A is the area of the fracture plane in m^2, and d is the mean particle diameter in m.

4 MODEL VALIDATION USING EXPERIMENTAL DATA

To validate the erosion model with experiemental results, the erosion parameters calculated by the model have been plotted together with experimental results in Figs. 8 and 9. These plots confirm that the model can capture accurately the erosion behaviour of the soil for a wide range of hydraulic shear stresses.
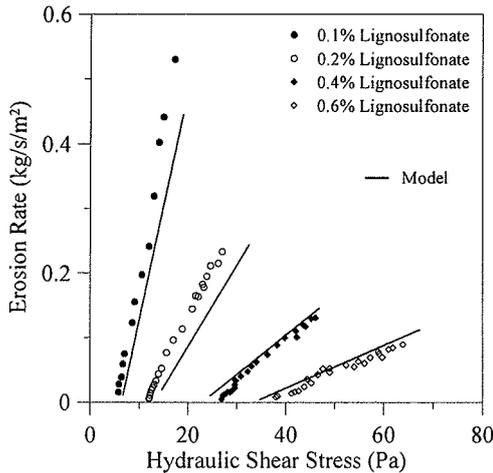
Figure 8. Experimental result versus model prediction for lignosulfonate treated erodible soil (Indraratna *et al.*, 2009).
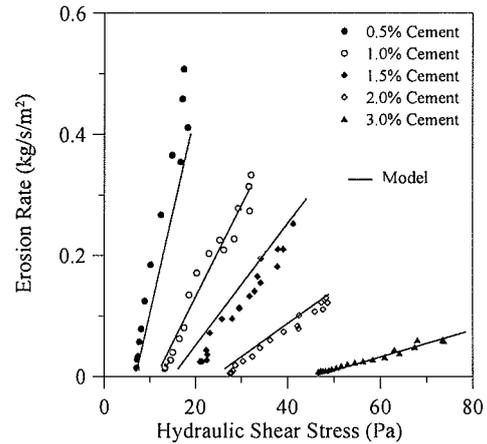
Figure 9. Experimental result versus model prediction for cement treated erodible soil (Indraratna *et al.*, 2009).

5 MICRO-CHEMICAL ANANLYSIS

Micro-chemical analysis was performed on lignosulfonate treated erodible soil using X-ray diffraction analysis (XRD) and Fourier Transform Infrared (FTIR) Spectroscopy by Vinod *et al.*

2010. The XRD anaysis has been performed on lignouslfnate treated erodible soil to determine the formation of new compounds due to lignosulfonate treatment. The XRD analysis revealed that there was no peak observed in the treated soil i.e no new compounds were formed due to treatment. Vinod *et al.* (2010) postulated that lignosulfonate-clay minerals interaction might form highly amorphous or non-crystalline compounds, which were very difficult to capture by the XRD analysis. The crystalline sizes of the clay minerals were determined from the XRD data using the following equation (Drits *et al.*, 1997):

$$L = \frac{\lambda k}{\beta \cos \theta}$$ (11)

Where, L is the mean crystalline dimension (crystalline size) along a line normal to the reflecting plane (Å); k is a constant nearly unity; λ is the wavelength of the X-radiation (1.54051Å); and β is the width of a peak at half height (radians of 2θ).

Table 1. XRD result of treated and untreated erodible soil (after Vinod *et al.*, 2010)

Type of clay mineral	Crystalline size (reflection of basal 001 plane) in nm		% reduction of crystalline size
	Erodible soil	Erodible soil treated with 1% lignosulfonate	
Kaolinite	13.87	11.55	16.73
Montmorillonite	154.28	43.25	71.97
Quartz	37.79	36.32	3.89
Illite	31.55	16.10	48.97

The mean crystalline sizes of clay minerals measured from full width half maximum (FWHM) of XRD peaks are presented in Table 1. It can be seen from Table 1 that the percentage reduction of crystalline size varied with the type of clay minerals in order of montmorillonite>illite>kaolinite. Vinod *et al.* (2010) highlighted that the reduction in clay mineral size depended on the clay structure and interstitial bonding of clay minerals. Moreover, the constant peak position of treated and untreated clay minerals indicated that there was no change of crystalline orientation due to the treatment by lignosulfonate. This demonstrated that crystalline size reduction occurred due to the reduction of surface negative charges by lignosulfonate. Therefore, surface charge of clay minerals for lignosulfonate treated soil still needs to be investigated by other chemical analysis.

Vinod *et al.* (2010) also performed FTIR analysis on treated and untreated erodible soil in the wave number ranging from 4000 to 800 cm^{-1} to investigate the micro-structural change of lignosulfonate treated soil. They observed a clear difference in spectra in the wave number ranging from 2000 to 1200 cm^{-1} in the FTIR results of treated soil when compared with untreated soil (Figure 10). The additional spectra observed in the FTIR results of lignosulfonate-treated soil confirms the presence of functional groups such as benzene (1650, 1517 cm^{-1}) and the CH group (1460 cm^{-1}). The presence of the functional groups of lignosulfonate in soil indicates the formation of ionic bonding between the clay mineral lattices and the lignosulfonate functional groups, as well as the existence of lignosulfonate in the interlayer spacing of soil minerals.

6 STABILIZATION MECHANISM OF LIGNOSULFONATE TREATED DISPERSIVE SOIL

A schematic diagram (Fig. 11) explaining the mechanism of lignosulfonate treated soil has been developed based on the FTIR and XRD analysis. Fig. 11a shows the untreated soil particles with negative charges in the interstitial layer of clay minerals. Once the lignosulfonate is mixed with water, it participates in hydrolysis reaction resulting positively charged compounds. The detailed hydrolysis reaction can be found elsewhere (e.g. Vinod *et al.*, 2010).
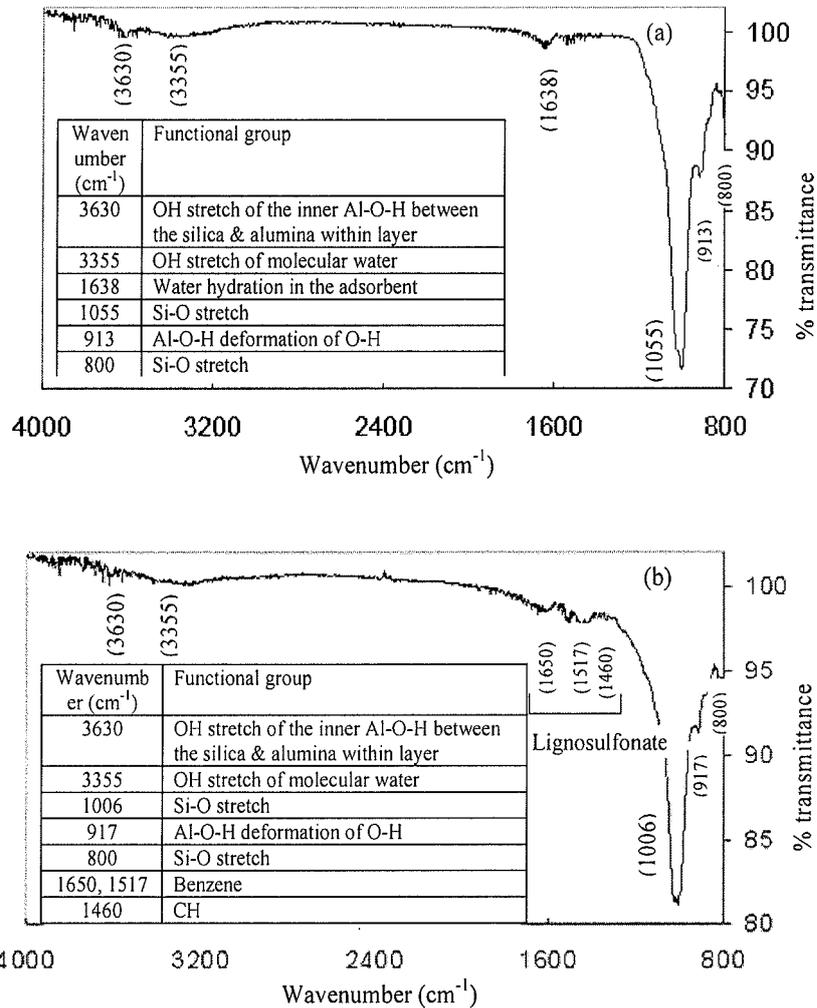
Wavenumber (cm⁻¹)	Functional group
3630	OH stretch of the inner Al-O-H between the silica & alumina within layer
3355	OH stretch of molecular water
1638	Water hydration in the adsorbent
1055	Si-O stretch
913	Al-O-H deformation of O-H
800	Si-O stretch

Wavenumber (cm⁻¹)	Functional group
3630	OH stretch of the inner Al-O-H between the silica & alumina within layer
3355	OH stretch of molecular water
1006	Si-O stretch
917	Al-O-H deformation of O-H
800	Si-O stretch
1650, 1517	Benzene
1460	CH

Figure 10. (a) FTIR result of dispersive clay; (b) lignosulfonate treated dispersive soil (Vinod et al., 2010).

When the lignouslfonate-water mixture is mixed with the soil (Fig. 11b), the positively charged lignosulfonate is adsorbed on the surface of clay minerals and forms bonding by electrostratic attraction. Positively charged lignosulfonate is attracted by negative charged clay mineral, resulting in the reduction of interstial double layer water (Fig. 11c). Then the lignosulfonate polymer chain binds the soil particles together and forms soil aggregates (Fig. 11d). The formation of soil aggregates by lignosulfonate treatment has been confirmed using SEM images of treated erodible soil presented by Indraratna *et al.* (2008).
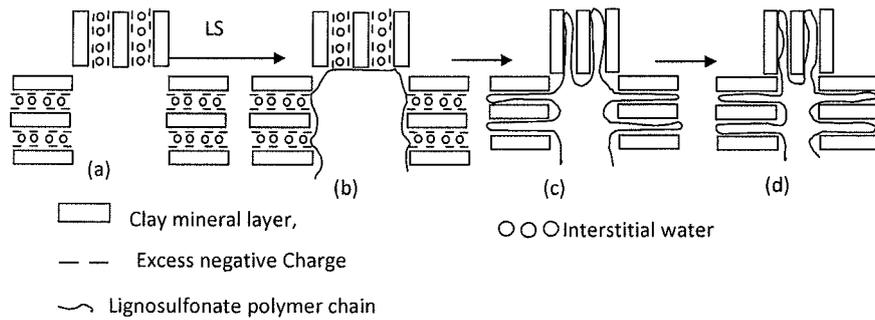
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Figure 11. Schematic diagram of stabilization mechanism for lignosulfonate treated soil (Vinod *et al.*, 2010)

7 CONCLUSIONS

This paper highlights the potential of lignosulfonate in stabilsing the erodible soil, which is commonly found in NSW, Australia. It was found that the chemical stabilisers reduced the coefficient of soil erosion and significantly increased the critical shear stress. It was also observed that significantly less amount of lignosulfonate than cement was sufficient to achieve a given increase in the erosion resistance. The coefficient soil erosion of erodible soil decreased from 0.265 to 0.002 with the addition of 3.0 % cement, whereas it decreased by approximately 85 times with the addition of 0.6 % lignosulfonate. An analytical model was developed to capture the tensile behaviour based on the law of conservation of energy. The erosion rate of saturated chemically stabilised soil can be calculated using the proposed model if the tensile force-deformation characteristics, dry density, mean particle diameter, and mean flow velocity are known. Validation using the experimental results from both tensile and erosion tests showed that only a fraction of energy from the water stream was used for erosion. It has been found that the proposed model is capable of capturing the erosion process accurately for a wide range of hydraulic shear stress. Moreover, micro-chemical analysis reveals that the improvement of performance exhibited by the lignosulfonate treated soil is attributed to the reduction of the double layer thickness by the neutralization of surface charges of the clay particles and the subsequent formation of a stable particle cluster or aggregate.

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