

University of Wollongong

Research Online

Faculty of Engineering and Information
Sciences - Papers: Part A

Faculty of Engineering and Information
Sciences

1-1-2014

Erosion mitigation of lignosulfonate treated unstable soils

Buddhima Indraratna

University of Wollongong, indra@uow.edu.au

Rasika Manori Athukorala

University of Wollongong, rasika@uow.edu.au

J S Vinod

University of Wollongong, vinod@uow.edu.au

Follow this and additional works at: <https://ro.uow.edu.au/eispapers>



Part of the [Engineering Commons](#), and the [Science and Technology Studies Commons](#)

Recommended Citation

Indraratna, Buddhima; Athukorala, Rasika Manori; and Vinod, J S, "Erosion mitigation of lignosulfonate treated unstable soils" (2014). *Faculty of Engineering and Information Sciences - Papers: Part A*. 3107. <https://ro.uow.edu.au/eispapers/3107>

Research Online is the open access institutional repository for the University of Wollongong. For further information contact the UOW Library: research-pubs@uow.edu.au

Erosion mitigation of lignosulfonate treated unstable soils

Abstract

Highly unstable soils are common in many parts of the world. In recent years, traditional chemical admixtures such as cement, lime and fly ash were used for stabilising these soils. However, not all chemical stabilisers are readily acceptable due to stringent occupational health and safety issues and invariable change of soil pH that often limits the scope of vegetation plus imposing a threat to ground water pollution. However, recent research shows that lignosulfonate, an environmentally sustainable admixture, can stabilise unstable and erodible soils without causing adverse effects on the environment. This paper presents the results of a laboratory investigation and model predictions on the internal erosion behaviour of an unstable soil stabilised by lignosulfonate. Test results reveal that the erosion parameters such as the critical shear stress and coefficient of soil erosion were improved with the increased amount of lignosulfonate. A theoretical model has also been developed to capture the internal erosion behaviour of soil based on the law of conservation of energy. The stabilization of the soil particles by lignosulfonate treatment is characterized by the increased strain energy required to break the inter-particle bonds. The model predictions capture the internal erosion behaviour of lignosulfonate treated soil similar to the laboratory experiments.

Disciplines

Engineering | Science and Technology Studies

Publication Details

Indraratna, B., Athukorala, R. & Vinod, J. S. (2014). Erosion mitigation of lignosulfonate treated unstable soils. In A. Bouazza, S. T. S. Yuen & B. Brown (Eds.), 7th International Congress on Environmental Geotechnics (pp. 793-800). Melbourne, Australia: Engineers Australia.

Erosion Mitigation of Lignosulfonate Treated Unstable Soils

B. Indraratna¹, R. Athukorala² and J. S. Vinod³

¹Professor of Civil Engineering and Research Director, Centre for Geomechanics and Railway Engineering, University of Wollongong, Wollongong, NSW 2522, Australia ; email: indra@uow.edu.au

²Research Associate, Centre for Geomechanics and Railway Engineering, University of Wollongong, Wollongong, NSW 2522, Australia; email: parma975@uowmail.edu.au

³Senior Lecturer, Centre for Geomechanics and Railway Engineering, University of Wollongong, Wollongong, NSW 2522, Australia; email: vinod@uow.edu.au

ABSTRACT

Highly unstable soils are common in many parts of the world. In recent years, traditional chemical admixtures such as cement, lime and fly ash were used for stabilising these soils. However, not all chemical stabilisers are readily acceptable due to stringent occupational health and safety issues and invariable change of soil pH that often limits the scope of vegetation plus imposing a threat to ground water pollution. However, recent research shows that lignosulfonate, an environmentally sustainable admixture, can stabilise unstable and erodible soils without causing adverse effects on the environment. This paper presents the results of a laboratory investigation and model predictions on the internal erosion behaviour of an unstable soil stabilised by lignosulfonate. Test results reveal that the erosion parameters such as the critical shear stress and coefficient of soil erosion were improved with the increased amount of lignosulfonate. A theoretical model has also been developed to capture the internal erosion behaviour of soil based on the law of conservation of energy. The stabilization of the soil particles by lignosulfonate treatment is characterized by the increased strain energy required to break the inter-particle bonds. The model predictions capture the internal erosion behaviour of lignosulfonate treated soil similar to the laboratory experiments.

Keywords: soil erosion, erosion rate, chemical stabilisation, lignosulfonate, silty sand

1 INTRODUCTION

In Australia and worldwide, highly unstable soils have been reported as a major problem initiating failure of earth structures including rail/road embankments, dam cores, and water channels. Chemical stabilisation using additives such as lime, cement, gypsum, slag, alum, and fly ash has been proven to be an appropriate and cost effective technique to stabilise these unstable soils (Perry 1977; Ryker 1977; Machan et al. 1977; Indraratna et al. 1991; Indraratna 1996; Biggs and Mahony 2004; Indraratna et al. 2008a,b; Indraratna et al. 2009). However, these traditional soil stabilisers have been identified to cause serious environmental problems such as changing the soil pH and ground water, and cause negative impact on agriculture and aquaculture (Little 1995; West and Carder 1999; Rollings et al. 1999; Hassan et al. 2008; Kitazume and Terashi 2013). The traditional additives also have adverse effects on the chemical aspects (e.g, electrical conductivity and cation exchange capacity) of the natural soil and the soil fertility (Kitchen and Sudduth 1996; Boardman et al. 2001; Chen et al. 2009;). Moreover, traditionally treated soils tend to exhibit excessive brittleness that has clear implications on the stability of infrastructure, especially during cyclic and impact loading conditions prevailing in high speed rail and aircraft runways. In this context, lignosulfonate (LS), which is an environmentally friendly chemical admixture, was effective in stabilising some problematic soils (Pengelly et al. 1997; Puppala and Hanchanloet 1999; Tingle and Santori 2003). Lignosulfonate is a lignin based organic polymer derived as a waste by- product from the paper manufacturing industry. Commercially available forms of lignin are Calcium, Sodium, Magnesium and Ammonium lignosulfonates. Lignosulfonate is a non-corrosive and non-hazardous chemical that does not change the soil pH upon treatment. Preliminary investigations show that the lignosulfonate treatment increases both the compressive and tensile strength of soil and the amount of lignosulfonate required to stabilize soft or unstable soils is much less compared to traditional admixtures (Indraratna et al 2008a & b). So far only a few studies have been reported in the literature, hence, the erosion resistance behaviour of unstable soil stabilised by lignosulfonate is still not well understood.

Calculating the erosion rate, i.e., the amount of soil eroded in unit time over a unit surface area, of chemically stabilised soil is an effective approach to evaluate the safety of earth structures in order to eliminate the possibility of erosion after construction. Only a few researchers have attempted to model soil erosion incorporating shear or tensile strength of soil (e.g. Dunn 1959; Lyle and Smerdan 1965; Hjeldnes and Lavinia 1980; Kamphuis and Hall 1983; Reddi and Bonala 1997). Most of these models are empirical, but Indraratna et al (2009) developed an analytical model to simulate the internal erosion of soil by capturing its tensile behaviour. However, the tensile strength tests are only suitable for soils that become cohesive during chemical treatment. Hence, it is essential to develop a comprehensive theoretical erosion model that correlates erosion resistance with the most widely used soil properties such as shear strength of chemically treated soil. Such a model will be widely applicable and be suitable for both cohesive and non-cohesive soils. In this paper, results of the of the internal erosion tests carried out using the Process Simulation Apparatus for Internal Crack Erosion (PSAICE) has been reported, A novel theoretical model was formulated to predict the erosion rate in terms of the effective shear strength parameters for lignosulfonate treated soil.

2 LABORATORY EROSION TESTS

2.1 Materials and test procedure

Indraratna et al (2008a) has carried out a series of laboratory internal erosion tests on an unstable soil collected from Wombayen Caves, Australia. This soil is classified as a non-plastic silty sand (SM) according to the Unified Soil Classification System. The liquid limit and the specific gravity of the soil were found to be 22.5% and 2.67, respectively. Particle size distribution curve of Wombayen caves silty sand is shown in Figure 1. From the standard proctor compaction tests the maximum dry density (MDD) and the optimum moisture content (OMC) were found to be 18.03 kN/m³ and 11.6%, respectively. Based on the findings of Muttuvel (2008), the effect of lignosulfonate on OMC and MDD is negligible for Wombayen caves silty sand and therefore, it was assumed here that those values for both LS treated and untreated soils are same. Furthermore, from the standard pinhole test this soil is classified as D1 (highly erodible soil). Lignosulfonate is a dark brown liquid with a specific gravity of 1.2 and a pH value of 3.8. It is completely soluble in water, non-flammable and non-toxic. Also, it is a non-corrosive chemical and is classified as non-hazardous according to the National Occupational Health and Safety Commission (NOHSC) criteria (Chemstab 2003; Muttuvel 2008; Indraratna et al 2013).

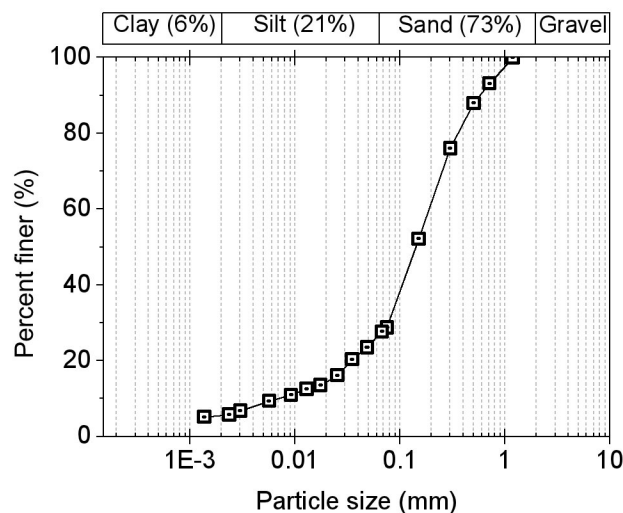


Figure 1. Particle size distribution curve of silty sand from Wombayen caves (after Indraratna et al 2013)

Various amounts of lignosulfonate (0.2-0.6% by dry soil weight) were mixed with the required amounts of water to obtain the OMC. Then, the lignosulfonate and water mixture was added into the selected silty sand and mixed thoroughly. Subsequently, the soil sample was statically compacted to 95% MDD inside a copper mould with a diameter of 72mm and a height of 100mm. After preparing the soil specimens, they were wrapped in moisture proof bags and cured for seven days inside a moisture-controlled room. The cured samples were immersed in water to saturate before carrying out the

internal erosion test using the PSAICE. More details on the testing procedure using PSAICE can be found in Indraratna et al (2008b).

2.2 Results and discussion

Figure 2 illustrates the variations of erosion rates with the applied hydraulic shear stresses for lignosulfonate treated and untreated silty sand. It is evident from Figure 2 that the rate of soil erosion follows a linear relationship with applied hydraulic shear stress for both lignosulfonate treated and untreated soils. The critical shear stress required to initiate soil erosion increased with the increasing amount of lignosulfonate. Furthermore, the coefficient of soil erosion, which is taken as the slope of the straight-line, decreased due to lignosulfonate stabilisation. The variation of the erosion parameters, critical shear stress initiating erosion and the coefficient of soil erosion, is shown in Figure 3. With the addition of 0.6% lignosulfonate, the critical shear stress has increased from 0.75 to 34.5 Pa while the coefficient of soil erosion decreased from 0.230 to 0.0031 s/m.

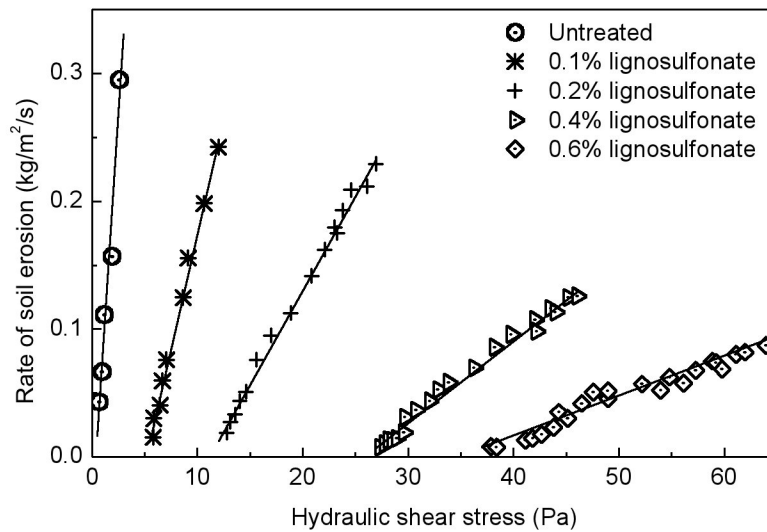


Figure 2. Variation of erosion rates of lignosulfonate treated and untreated silty sand with applied hydraulic shear stress (after Indraratna et al 2008b)

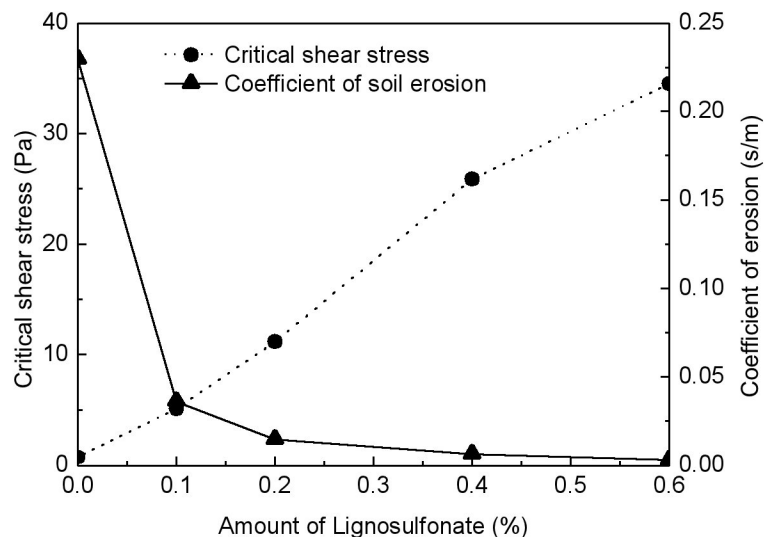


Figure 3. Variation of critical shear stress and coefficient of soil erosion with the amount of lignosulfonate

3 PROPOSED EROSION MODEL

The proposed erosion model is based on the energy conservation principle according to which the energy dissipated by the excess hydraulic shear stress during erosion should be equal to energy required by the soil particles to erode. The energy required by the soil to erode was formulated considering that rolling is the predominant mechanism by which the soil particles are detached from the soil bed due to lift and drag forces. When the hydrodynamic forces act on the chemically bonded particles exceed a critical value, the inter-particle bonds are broken and the particle come into suspension. It was assumed that no re-settlement takes place once the particles are fully suspended reaching the flow velocity. The lignosulfonate stabilization was taken into account through the increased strain energy, which is an indication of the energy required to break the inter-particle bonds between soil grains.

3.1 Formulation of soil erosion

The energy required by a single soil grain (E_b^*) to break the inter-particle bonds was formulated by considering the work done by applied normal and shear forces on that grain, and expressed by:

$$E_b^* = qD^2A^* \left(1 - \frac{2}{3} \sin(\phi')^* \tan \beta \right) \quad (1)$$

where, q and β are constants that depends on the packing arrangement of particles, D is the mean particle diameter, $(\phi')^*$ is the internal friction angle of treated soil and A^* is determined from the strain energy density of soil up to failure using the stress-strain curves.

To formulate the energy required for a particle (E_s) to come into suspension, it was considered that the movement of the particle consists of two distinct processes; (i) it will roll on the contact particle until the contact is lost, (ii) it will be lifted while moving with the fluid until it reaches the flow velocity. After applying the equations of motion to a single soil grain, E_s can be given by:

$$E_s = m \left\{ \frac{[V_t^2]_{(\varphi=\varphi_{max})}}{5} + \frac{V_f^2}{2} \right\} \quad (2)$$

where, m is the mass of a single soil grain, V_t is linear velocity of the moving soil particle in tangential direction, φ is the angle by which the moving particle has rolled on the contact particle and V_f is the mean flow velocity.

To determine the rate of soil erosion, an infinitesimal volume (dv) of soil inside a crack of a soil specimen subjected to erosion was considered (Figure 4). It was assumed that the erosion is uniform over the crack surface and the rate of change of the crack radius is linear over the time.

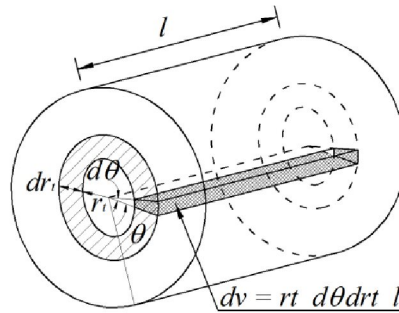


Figure 4. Change in the crack radius due to erosion (after Indraratna et al. 2013)

Now, the total energy (E_T) required by a dv volume of soil for erosion can be expressed as:

$$E_T = \frac{12\rho_d}{G_s\rho_w\pi D^3} r_t dr_t l \int_0^\pi (E_b^* + E_s) d\theta \quad (3)$$

where, G_s and ρ_d are the specific gravity and dry density of soil, respectively and ρ_w is the density of eroding fluid. According to the principle of conservation of energy, the total energy (E_T) given by

Equation (3) was taken to be equal to the energy dissipated (ΔE) by the excess hydraulic shear stress. An expression for ΔE was given by Muttuvél (2008) as:

$$\Delta E = \omega(\tau_a - \tau_c)V_f 2\pi r_t l dt \quad (4)$$

where, ω is the efficiency factor, τ_a is applied hydraulic shear stress and τ_c is critical shear stress initiating erosion. Then, Equations (3) and (4) were evaluated for dr_t/dt and multiplied by ρ_d to obtain the rate of soil erosion that is defined as the amount of soil eroded in unit time over a unit surface area (Muttuvél 2008). The erosion rate, $(\dot{\epsilon})^*$, of lignosulfonate treated soil can now be given as:

$$(\dot{\epsilon})^* = \left[\frac{G_s \rho_w \omega V_f}{\frac{6q}{\pi D} A^* \left(1 - \frac{2}{3} \sin \phi'^* \tan \beta\right) + \frac{G_s \rho_w}{12} V_f^2} \right] (\tau_a - \tau_c^*) \quad (5)$$

More details on the formulation of this erosion model can be found elsewhere (Indraratna et al. 2013).

3.2 Parameter calculation and model validation

In order to validate the proposed erosion model, a series of consolidated drained direct shear tests were carried out on lignosulfonate treated and untreated soil specimens. The shear tests were conducted at the same moisture content (OMC) and dry density (95% MDD) conditions used in the erosion tests to ensure reliability between the shear and erosion tests. Three lignosulfonate dosages (0.2%, 0.6% and 1.2% by dry soil weight) and five effective normal stresses (5kPa, 10kPa, 15kPa, 22kPa and 42kPa) were selected to obtain the shear behaviour of stabilized soil. The required amount of lignosulfonate was mixed with water before adding into soil. The samples were compacted statically, cured for seven days and saturated for 24 hours in the sample container prior to subjecting to shear under constant shearing rate of 0.05mm/min.

The strain energy per unit volume up to peak stress (i.e. area beneath the stress-strain curve), used to determine the value of A^* , was calculated for lignosulfonate treated and untreated soil and is given in Figure 5. It is evident from Figure 5 that the strain energy per unit volume has increased as a result of lignosulfonate treatment for all the effective normal stresses considered in this study.

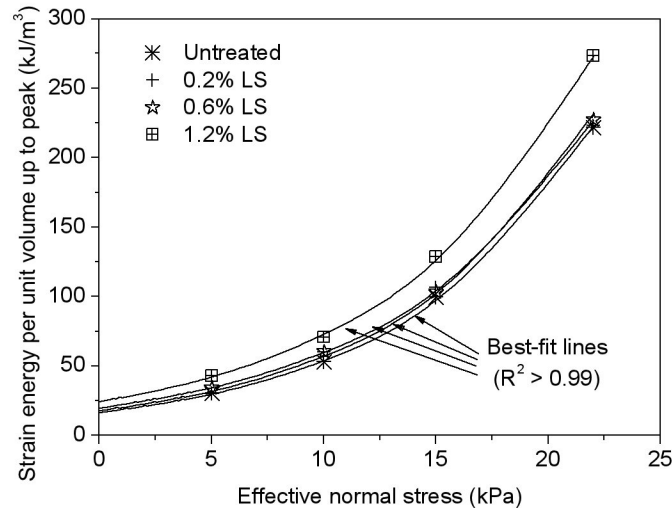


Figure 5. Variation of strain energy per unit volume up to peak with effective normal stress (after Indraratna et al 2013)

To validate Equation (5) and calculate the rate of erosion of LS stabilised soil, the model parameters A^* , the internal friction angle of soil (ϕ'^*) at $\sigma'_n = 0$, the critical shear stress (τ_c^*) initiating erosion, and the efficiency factor (ω) should be estimated first. The first two parameters (A^* and ϕ'^*) were determined from the shear test results as shown in Figures 6(a) and 6(b), respectively and the other two parameters (τ_c^* and ω) were found from the results of the erosion tests as illustrated in Figures 6(c) and 6(d), respectively.

The parameters q and β in Equation (5) represent the packing arrangement of the particles of soil before they are eroded. To determine suitable values for these parameters, the packing arrangement of the soil particles within the compacted soil mass should be identified. For this purpose, the soil particles were assumed to be spherical in shape. The soil specimens for both the direct shear and internal erosion tests were prepared at OMC and 95% MDD maintaining the consistency in packing structure. The value of the porosity of those specimens was calculated to be 29%. Therefore, the tetragonal packing arrangement (Gray 1968) was identified as the closest possible packing structure for the specimens in this study. Consequently, q and β were calculated for the tetragonal packing structure, as illustrated in Figure 7.

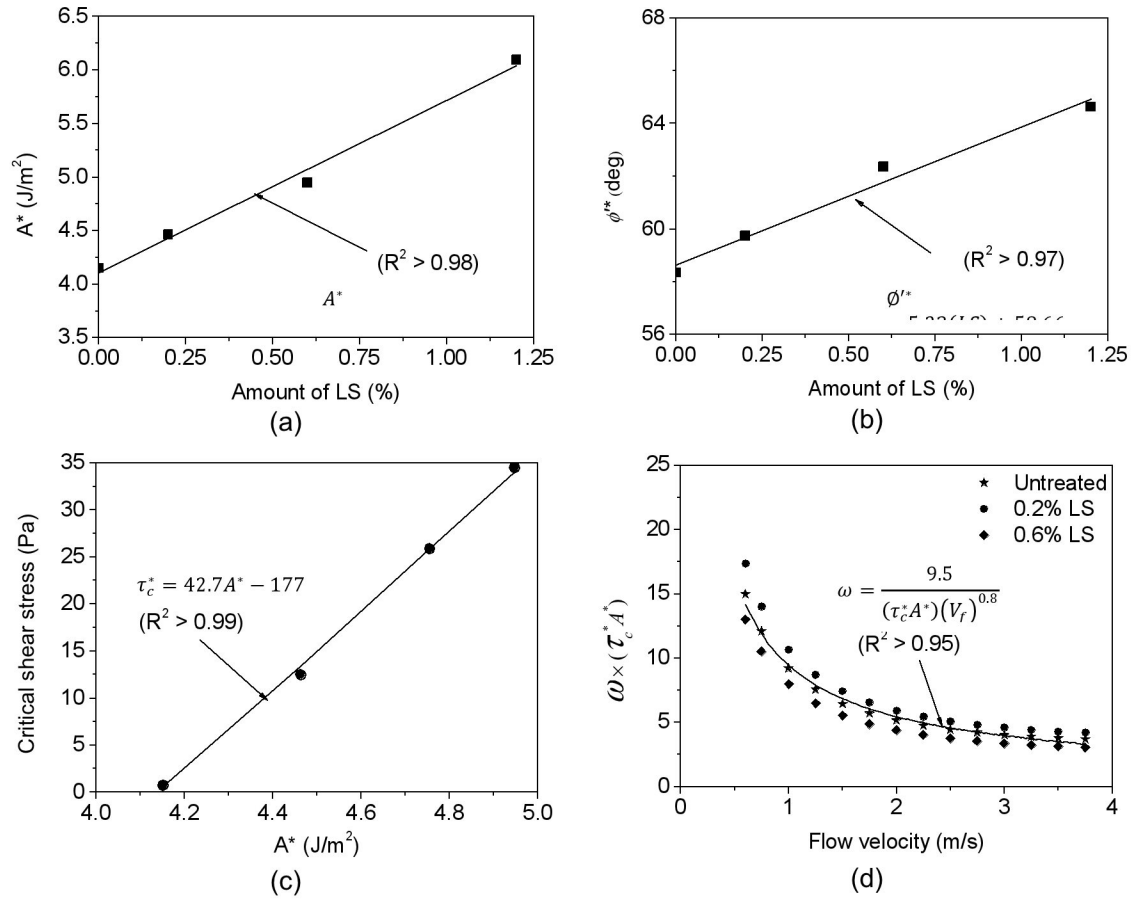


Figure 6. Determination of erosion model parameters (A^* , ϕ^{*} , τ_c^* and ω) (after Indraratna et al 2013)

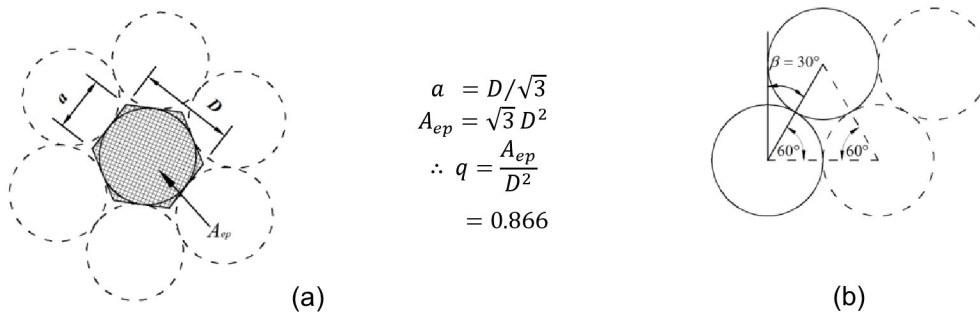


Figure 7. Estimating (a) the value of q (b) the value of β for tetragonal packing arrangement of spheres (after Athukorala 2013)

To verify that the proposed equation is capable of predicting the erosion rate of soil for different amounts of lignosulfonate treatment over a wider range of hydraulic shear stresses, the erosion rates

predicted by the model for untreated, 0.1%, 0.2%, 0.4% and 0.6% LS treated silty sand were plotted against the hydraulic shear stress. Also, these predicted results were compared with the erosion rates for treated and untreated specimens that were observed in the laboratory (Figure 8). A range of mean flow velocities were used to generate different hydraulic shear stresses for a given level of lignosulfonate treatment. In Figure 8, the 0.1%, and 0.4%LS treated predictions are completely independent as these experimental results were not used to determine the model parameters. A comparison between the erosion parameters of untreated and treated silty sand obtained experimentally and predicted by the proposed model is shown in Table 1. It is evident from Table 1 that the proposed erosion model can accurately capture the erosion of untreated soil and soil stabilised by lignosulfonate over a wide range of hydraulic shear stresses.

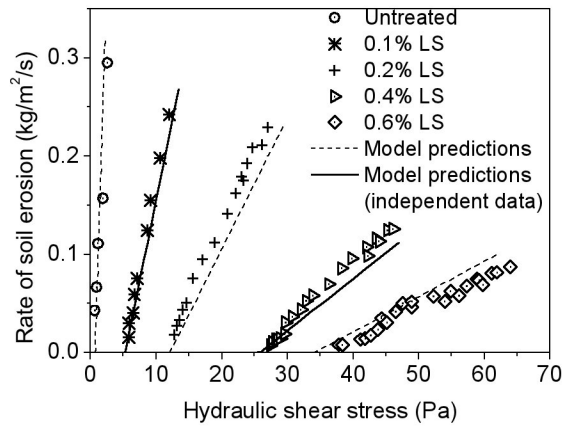


Figure 8. Comparison of experimental and model predicted erosion rates (after Indraratna et al 2013)

Table 1. Comparison of observed and model predicted erosion parameters

% LS	Critical shear stress (Pa)		Coefficient of erosion (s/m)	
	observed	predicted	observed	predicted
0	0.75	0.71	0.229	0.214
0.1	5.14	5.24	0.036	0.033
0.2	11.15	12.03	0.015	0.013
0.4	25.89	25.85	0.006	0.005
0.6	34.52	34.01	0.003	0.004

4 CONCLUSION

This paper presents the results of a study on the internal erosion behaviour of LS treated soil. Laboratory experiments carried out using PSAICE highlight that the lignosulfonate treatment reduces the coefficient of soil erosion significantly while increasing the critical shear stress required to initiate erosion. The rates of soil erosion of both lignosulfonate treated and untreated silty sand vary linearly with the applied hydraulic shear stress. Based on the laboratory findings, a novel theoretical erosion model, incorporating the strain energy, has been proposed for lignosulfonate treated soils. Empirical expressions were derived to compute the values of the key parameters such as A^* , ϕ'^* , τ_c^* and ω used for the model. The parameter A^* , which depends on strain energy density at $\sigma'_n = 0$, and ϕ'^* were found to be linearly related to the amount of lignosulfonate. Also, a linear relationship was obtained between critical shear stress required to initiate erosion and the parameter A^* . The efficiency factor (ω) was observed to be decreasing with the increasing flow velocity for both lignosulfonate treated and untreated silty sand. However, it decreases with the increasing amount of lignosulfonate for a given flow velocity. The efficiency factor, normalised by the corresponding values of A^* and τ_c^* , can be given by a single decaying power function of the flow velocity, irrespective of the amount of lignosulfonate. The erosion rates were predicted for lignosulfonate treated silty sand using the expressions obtained for A^* , ϕ'^* , τ_c^* , and ω (Eq. 5) and compared with the laboratory erosion test results. The proposed erosion model can estimate the erosion rate over a wide range of hydraulic shear stress for different amount of LS similar to the laboratory experiments. This model can be adopted in practice to evaluate internal erosion in assessing the safety of earth structures such as rail/road embankments and dam cores. Practising engineers can use the relationship between the erosion rates and the applied hydraulic shear stress to determine the amount of lignosulfonate to be mixed with the material before compaction, in order to eliminate the possibility of erosion after construction.

5 ACKNOWLEDGEMENTS

The authors acknowledge the financial assistance provided by the Australia Research Council (Australia), Queensland Department of Transport and Main Roads (Brisbane) and Robert Armstrong (Chemstab Consulting Pvt. Ltd., Wollongong). The assistance provided by Mr. Alan Grant and Mr. Ian

Laird during the laboratory investigation is gratefully acknowledged. The authors also would like to thank Dr. Thevaragavan Muttuvel for providing the experimental data for the current study. More elaborate details of the contents discussed in the paper can also be found in previous publications of the first Author and his research students in ASCE and Canadian Geotechnical Journals, since the mid 1990's. Valuable comments from A/Prof Hadi Khabbaz of UTS are greatly appreciated.

REFERENCES

- Athukorala, R. (2013). "Geotechnical characteristics of an erodible soil stabilised by lignosulfonate – an analytical perspective". *School of civil, minning and environmental engineering*, University of Wollongong. Doctor of Philosophy: 204.
- Athukorala, R., Indraratna, B. and Vinod, J. S. (2013). Modeling the Internal Erosion Behavior of Lignosulfonate Treated Soil, *GEOCONGRESS 2013: Geotechnical Special Publication No. 231*, Meehan, C. L., Pradel, D., Pando, M. A. and Labuz, J. F. (Eds.) San Diego, USA, (4-6 March 2013), 19-33.
- Biggs, A. J. W. and Mahony, K. M. (2004). Is soils science relevant to road infrastructure? *ISCO 2004 - 13th International Soil Conservation Organisation Conference*, Brisbane, Australia, Conserving Soil and Water for Society: Sharing Solutions.
- Boardman, D. I., Glendinning, S., Rogers, C. D. F., Holt, C. C. and Trb (2001). In situ monitoring of lime-stabilized road subgrade. *Geomaterials 2001: Soils, Geology, and Foundations*. Washington, Transportation Research Board Natl Research Council: 3-13.
- Chemstab (2003). Technical Manual, Chemstab Consulting Pty Ltd, Horsley, NSW, Australia.
- Chen, R., Drnevich, V. P. and Daita, R. K. (2009). "Short-Term Electrical Conductivity and Strength Development of Lime Kiln Dust Modified Soils." 135(4): 590-594.
- Dunn, I. S. (1959). "Tractive resistance of cohesive channels." *Journal of the soil mechanics and foundations division ASCE* Vol. 85 (SM3): 1-24.
- Gray, W. A. (1968). The packing of solid particles. London, *Chapman and Hall Ltd*.
- Hassan, M. M., Lojander, M. and Ravaska, O. (2008). Characteristics of soft clay stabilized for construction purposes. *Advances in Transportation Geotechnics*, CRC Press: 651-656.
- Hjeldnes, E. I. and Lavinia, B. V. K. (1980). "Cracking, leakage and erosion of earth dam materials." *Journal of geotechnical engineering division ASCE* Vol. 106 (GT2): 117-135.
- Indraratna, B. (1996). "Utilization of lime, slag and fly ash for improvement of a colluvial soil in New South Wales, Australia." *Geotechnical and Geological Engineering* 14(Compendex): 169-191.
- Indraratna, B., Athukorala, R. and Vinod, J. S. (2013). "Estimating the rate of erosion of a silty sand treated with lignosulfonate." *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, 139(5), 701-714.
- Indraratna, B., Muttuvel, T. and Khabbaz, H. (2008a). Investigating erosional behaviour of chemically stabilised erodible soils, New Orleans, Louisiana, ASCE.
- Indraratna, B., Muttuvel, T. and Khabbaz, H. (2009). "Modelling the erosion rate of chemically stabilized soil incorporating tensile force - deformation characteristics." *Canadian Geotechnical Journal*: 57-68.
- Indraratna, B., Muttuvel, T., Khabbaz, H. and Armstrong, R. (2008b). "Predicting the erosion rate of chemically treated soil using a process simulation apparatus for internal crack erosion." *Journal of Geotechnical and Geoenvironmental Engineering* 134(6): 837-844.
- Indraratna, B., Nutalaya, P. and Kuganenthira, N. (1991). "Stabilization of a dispersive soil by blending with fly ash." *Quarterly Journal of Engineering Geology and Hydrogeology* 24(3): 275-290.
- Kamphuis, J. and Hall, K. (1983). "Cohesive material erosion by unidirectional current." *Journal of Hydraulic Engineering* 109(1): 49-61.
- Kitazume, M. and Terashi, M. (2013). The deep mixing method. Leiden, The Netherlands, *CRC Press/Balkema*.
- Kitchen, N. R., Sudduth, K. A. and Drummond, S. T. (1996). "Mapping of sand deposition from 1993 midwest floods with electromagnetic induction measurements." *Journal of Soil and Water Conservation* 51(4): 336-336.
- Little, D. N. (1995). Handbook for stabilization of pavement subgrades and base course with lime. Texas, USA, *Lime Association of Texas*.
- Lyle, W. M. and Smerdon, E. T. (1965). "Relation of compaction and other soil properties to erosion resistance of soils." *Transactions of the ASAE*: 419-422.
- Machan, G., Diamond, S. and Leo, E. (1977). "Laboratory study of the effectiveness of cement and lime stabilization for erosion control." *Transportation Research Record(Compendex)*: 24-28.
- Muttuvel, T. (2008). Erosion rate of chemically stabilised soils incorporating tensile stress-deformation behaviour. *School of civil, minning and environmental engineering*, University of Wollongong. Doctor of Philosophy: 216.
- Pengelly, A. D., Boehm, D. W., Rector, E. and Welsh, J. P. (1997). Engineering experience with in-situ modification of collapsible and expansive soils. *Unsaturated Soil Engineering Practice*. Houston, S. L. and D. G. Fredlund. New York, Amer Soc Civil Engineers: 277-298.
- Perry, J. P. (1977). "Lime treatment of dams constructed with dispersive clay soils." *Transactions of the American Society of Agricultural Engineers* 20(6): 1093-1099.
- Puppala, A. J. and Hanchanloet, S. (1999). evaluation of a new chemical (SA-44/LS-40) treatment method on strength and resilient properties of a cohesive soils Paper presented at Transportation Research Board annual meeting.
- Reddi, L. and Bonala, M. (1997). "Critical shear stress and its relationship with cohesion for sand-kaolin mixtures." *Canadian Geotechnical Journal* 34(1): 26-33.
- Rollings, R. S. and Burkes, M. P. (1999). "Sulfate attack on cement stabilized sand." *Journal of geotechnical and geoenvironmental engineering ASCE* 125(5): 364-372.
- Ryker, N. L. (1977). Encountering dispersive clays on soil conservation service projects in Oklahoma. *Dispersive clays, related piping and erosion in geotechnical projects*, ASTM STP 623. Sherard, J. L. and R. S. Decker, American society for testing and materials: 370-389.
- Tingle, J. S. and Santoni, R. L. (2003). Stabilization of clay soils with nontraditional additives. Washington, National Research Council. 1819: 72-84.
- West, G. and Carder, D. R. (1999). Review of Lime Piles and Lime-stabilised Soil Columns (Trl 305). London, UK, *Thomas Telford Ltd*.