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*Year 2008*

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This conference paper was originally published as Indraratna, B, Muttuvel T, and Khabbaz, H, Investigating Erosional Behaviour of Chemically Stabilised Erodible Soils, GeoCongress 2008, New Orleans, Geosustainability and Geohazard Mitigation GSP178, Reddy, KR, Khire, MV, Alshawabkeh, AN, (eds), 2008, 670-677.

This paper is posted at Research Online.

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## Investigating Erosional Behaviour of Chemically Stabilised Erodible Soils

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**ABSTRACT:** Chemical stabilisation is a popular technique to improve the erosion resistance of the soils. In this study, two chemical stabilisers, namely lignosulfonate and general purpose Portland cement were tested on two different soils, a silty sand and a dispersive clay. A series of erosion tests were performed to study the effectiveness of the stabilisation in increasing the erosion resistance. Results showed that the increase in the critical shear stress of the silty sand with only 0.6% lignosulfonate treatment was equivalent to that with around 2.5% cement treatment. However, the stabilisation of the dispersive clay with 0.6% cement was more effective than 0.6% lignosulfonate. The findings of this research also indicated that the coefficient of soil erosion decreased as a power function of the critical shear stress.

### INTRODUCTION

Erosion through internal cracks leading to piping and surface erosion are the most common erosion modes, which cause failures of earthdams and embankments. Hence, it is very important to improve the erosion resistance of soils using appropriate and cost effective techniques. Use of chemical admixtures is one way of increasing the erosion resistance of soil in earth structures. In the past, various stabilisers such as lime, cement, fly ash and milled slag were used as stabilising agents. The erosion of dispersive soils was controlled by adding lime and gypsum especially at the foundation-embankment interface and on the slope of the embankment (Biggs and Mahony 2004; Cole *et al.* 1977; Phillips 1977). Lime, milled slag, and fly ash can be used to reduce the erodibility of dispersive and colluvial soils (Indraratna 1996; Indraratna *et al.* 1991). However, limitations such as corrosion of steel structures adjacent to gypsum treated soils, and adverse effects on vegetation in the vicinity of lime treated soils due to high pH levels (Biggs and Mahony 2004; Perry 1977) have encouraged researchers to find alternative stabilisers.

Several studies were conducted in the past to understand the erosion mechanism and its dependability on different factors such as soil properties, and the properties of pore and eroding fluids. Wan and Fell (2004) performed erosion tests by applying hydraulic

gradient across a 6-mm soil hole to investigate the erosion characteristics of soil in cracks of embankment dams. They concluded that the erosion rate is directly influenced by the degree of compaction and placement water content. Sherard *et al.* (1976) developed the standard pinhole test to study the erosion characteristics of soil by pushing eroding fluid through a 1-mm crack.

In this study, a process simulation apparatus for internal crack erosion was designed and built at the University of Wollongong to evaluate the effectiveness of the chemical treatment on the erosional behaviour of different soils (a silty sand and a dispersive clay) treated with two chemical stabilisers, lignosulfonate and general purpose Portland cement. The details of the experimental investigation are discussed in the following section.

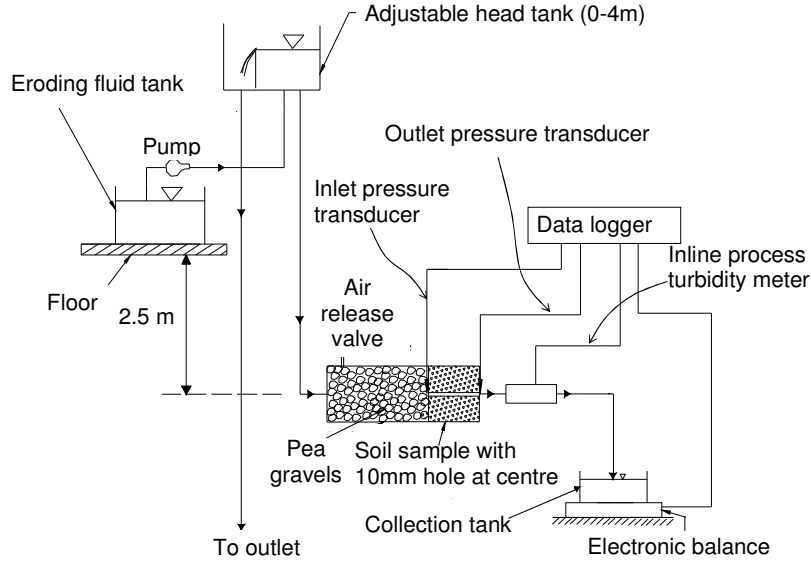
## **EXPERIMENTAL INVESTIGATION**

### **Properties of Soil and Chemical Stabilisers**

A silty sand collected from the area near Wombayen caves in New South Wales (NSW), Australia, and a dispersive clay collected from Wakool in NSW, Australia were selected for this study. According to the standard pinhole test (ASTM D4647), the silty sand and the dispersive clay are classified as D1 and D2, respectively. General purpose Portland cement manufactured in Australia, and lignosulfonate were selected for the experimental investigation. The lignosulfonate mixture is a completely soluble, dark brown liquid having a pH value of approximately 4. This stabiliser is inflammable, does not corrode metals, and is not classified as hazardous according to the National Occupational Health and Safety Commission (NOHSC) criteria (CHEMSTAB 2003).

### **Sample Preparation**

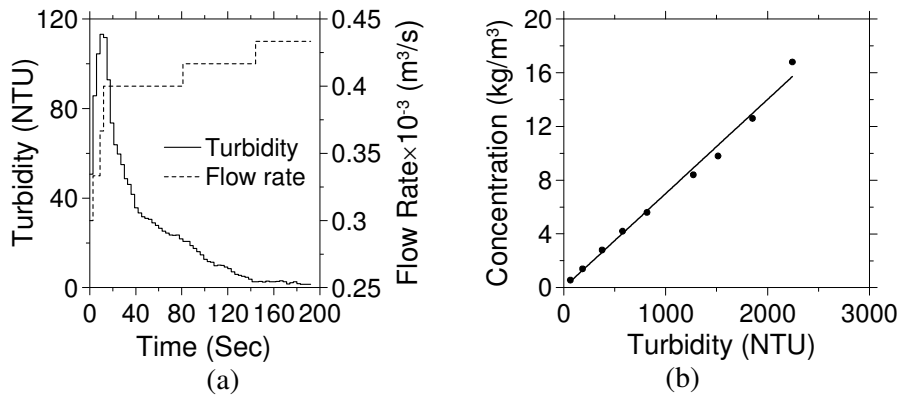
Four dosages of lignosulfonate, 0.1%, 0.2%, 0.4%, and 0.6% by dry weight of soil were selected to treat both soils. However, 0.5%, 1.0%, 1.5%, 2.0%, and 3.0% of cement were chosen to stabilise the silty sand, while 0.2%, 0.4%, and 0.6% dosages were selected to treat the dispersive clay. Each soil was mixed with the selected chemical additives and then it was compacted inside a 72mm diameter by 100mm long copper mould. After a seven-day curing, the samples were immersed in the eroding fluid (tap water) until they absorbed the maximum amount of water to become saturated. Erosion tests were carried out using newly built Process Simulation Apparatus for Internal Crack Erosion (*PSAICE*). The schematic diagram of the experimental set up is shown in Fig. 1. All tests were conducted by pushing the eroding fluid through a 10-mm soil crack formed at the centre of the samples. The eroding fluid was pumped into the moving constant head tank during testing. Two pressure transducers were connected to both ends of the sample to measure any difference in pressure across the crack. To continuously measure the erosion rate, an in-line process turbidity meter was connected next to the downstream side of the soil sample to constantly monitor the effluent turbidity during the erosion test. The turbidity values were then used with the relationship developed by the authors between the concentration of solids ( $\text{kg/m}^3$ ) and turbidity (NTU) of the selected soil to calculate the erosion rate. In order to continuously measure the flow rate, the effluent was weighed with an electronic balance. As shown in Fig. 1, all pressure transducers, the turbidity meter, and the electronic balance were connected to a data acquisition system.



**Fig. 1. Schematic diagram of process simulation apparatus for internal crack erosion**

### Interpretation of Observations

The observed flow rate and turbidity, and the relationship between concentration and turbidity for 0.4% lignosulfonate treated dispersive clay are given Fig. 2 (a) and (b), respectively.



**Fig. 2. (a) Observed turbidity and flow rate, and (b) relationship between concentration and turbidity for 0.4% lignosulfonate treated dispersive clay**

Based on the observations, the amount of soil eroded in a selected time interval  $\delta t$  is determined by:

$$\delta m = kQT \times \delta t \quad (1)$$

where,  $\delta m$  (kg) is the amount of dry soil eroded during a selected time interval  $\delta t$ ,  $Q$  ( $m^3/s$ ) is the average flow rate through the soil crack at time interval  $\delta t$ ;  $T$  (NTU) is the average turbidity of the effluent at  $\delta t$ ; and  $k$  ( $kg/m^3/NTU$ ) is the empirical factor relating turbidity to the soil solids concentrated in the flow. The value of  $k$  for untreated

and cement treated silty sand, determined based on the linear relationship, was 0.013 kg/m<sup>3</sup>/NTU. A slightly smaller value of  $k$  (0.011 kg/m<sup>3</sup>/NTU) was obtained for lignosulfonate treated silty sand. However, a range of  $k$  values (0.002-0.011) was obtained for treated and untreated dispersive clay. When the diameter of the soil crack changes by  $\delta\phi_t$  in a time interval  $\delta t$ , the amount of soil eroded during this time will be:

$$\delta m = \frac{\pi\phi_t l \rho_d}{2} \times \delta\phi_t \quad (2)$$

where,  $\rho_d$  (kg/m<sup>3</sup>) is the dry density of compacted soil;  $l$  (m) is the length of the soil crack; and  $\phi_t$  (m) is the diameter of the soil crack at time  $t$ .

Combining Equations (1) and (2) yields:

$$\delta\phi_t = \frac{2kQT}{\pi\phi_t l \rho_d} \times \delta t \quad (3)$$

Equation (3) can be used to calculate the change in diameter of the soil crack during erosion for each time interval using the flow rate, turbidity of effluent, and initial diameter of the soil crack. The erosion rate,  $\dot{\varepsilon}$  (kg/s/m<sup>2</sup>), can then be calculated using Equation (4):

$$\dot{\varepsilon} = \frac{kQT}{\pi\phi_t l} \quad (4)$$

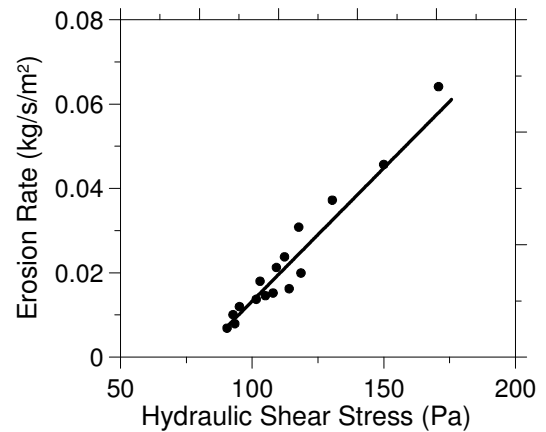
The hydraulic shear stress,  $\tau$  (Pa), on the soil crack surface can be calculated from:

$$\tau = \frac{\rho_w g i \phi_t}{4} \quad (5)$$

where,  $\rho_w$  (kg/m<sup>3</sup>) is the density of the eroding fluid;  $g$  (m/s<sup>2</sup>) is the gravitational acceleration; and  $i$  is the hydraulic gradient across the soil crack.

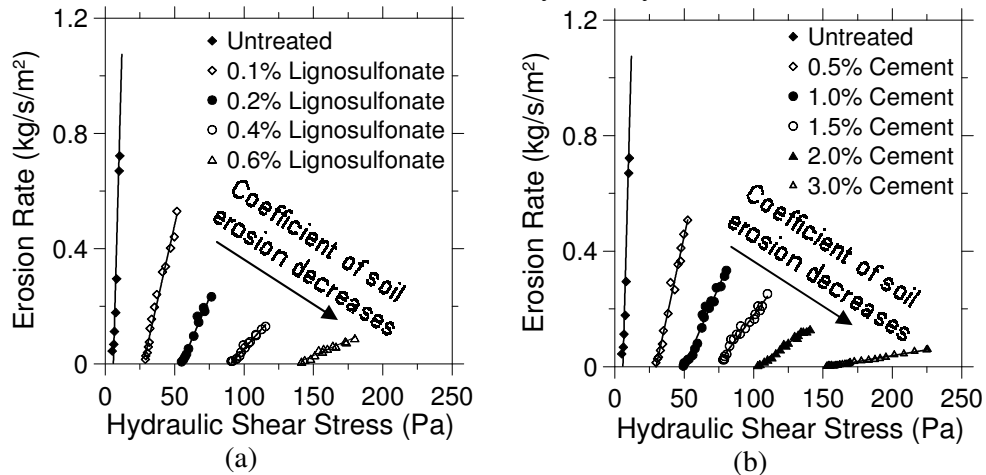
## RESULTS AND DISCUSSION

The predicted erosion rate against the hydraulic shear stress for 0.4% lignosulfonate treated dispersive clay compacted at 95% of the maximum dry density is plotted as shown in Fig. 3, where the erosion rate increases almost linearly with the hydraulic shear stress. A similar behaviour has also been reported by other researchers (Arulananthan *et al.* 1975; Sargunan 1977). In this study, the critical shear stress,  $\tau_c$ , is defined as the minimum hydraulic shear stress necessary to initiate erosion. It will therefore be determined by extrapolating a straight line to the zero erosion rate. The slope of this straight line

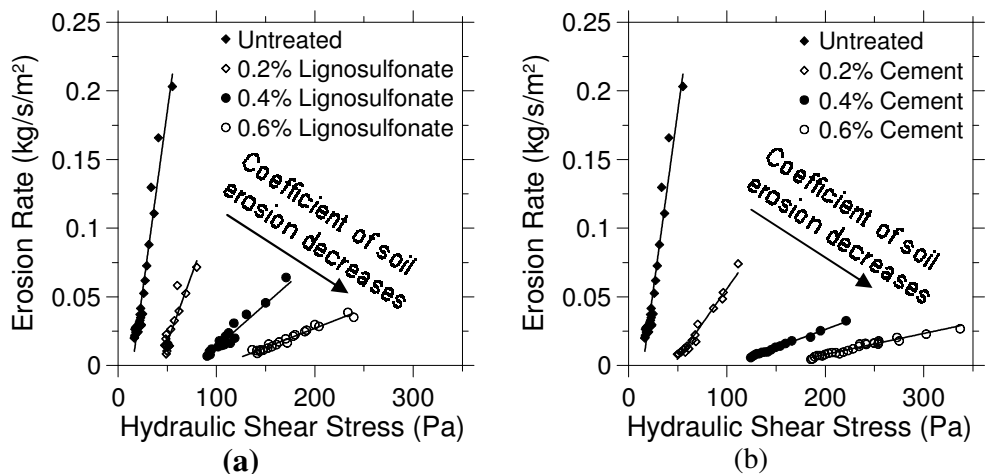


**Fig. 3. Erosion rate versus hydraulic shear stress for 0.4% lignosulfonate treated dispersive clay**

is presumed to be the coefficient of soil erosion. Hence, the predicted critical shear stress and the coefficient of soil erosion for 0.4% lignosulfonate treated dispersive clay are 79.1 Pa and 0.00063, respectively. It was observed that the variation of erosion rate with the hydraulic shear stress is linear for all other treated and untreated soil samples compacted at 95% and 90% of the maximum dry density.



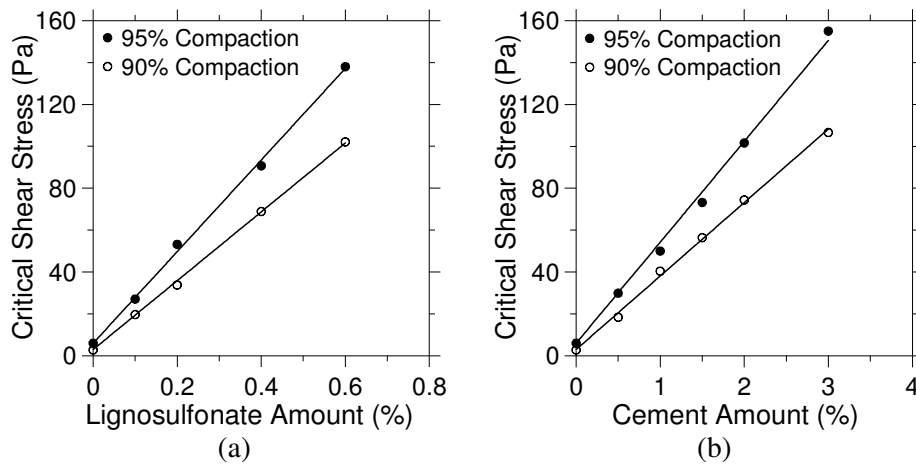
**Fig. 4. Erosion rate versus hydraulic shear stress for (a) lignosulfonate treated and untreated (b) cement treated and untreated silty sand**



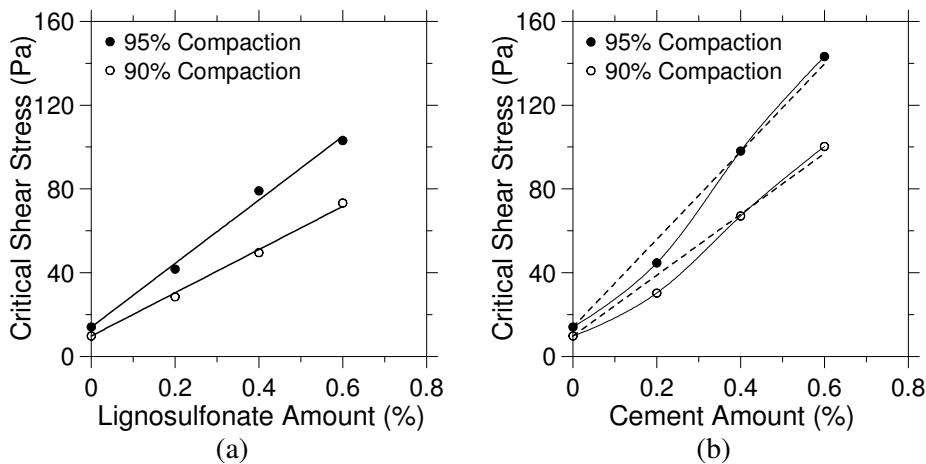
**Fig. 5. Erosion rate versus hydraulic shear stress for (a) lignosulfonate treated and untreated (b) cement treated and untreated dispersive clay**

Fig. 4 indicates the variation of the erosion rate with the hydraulic shear stress for the silty sand treated with two chemical stabilisers (compacted at 95% relative density). With increased levels of chemical additives, the coefficient of soil erosion decreases, as expected. It is noted that the critical shear stress also increases with the amount of chemical additives. Since untreated silty sand is non-cohesive and all treated and untreated soils were compacted at the same dry density and kept under the same curing conditions, it could be argued that the only possible cause for an increase in the erosion resistance of treated silty sand compared to untreated was the enhancement of cohesion attributed to cementation. For the silty sand, significantly less amount of lignosulfonate compare to cement is required to achieve a given increase in the critical shear stress. The behaviour of lignosulfonate and cement treated dispersive clay is shown in Fig. 5. It

illustrates that 0.6% cement treatment increases the critical shear stress of the dispersive clay more than 0.6% lignosulfonate treatment. This behaviour differs from that was observed for the silty sand. If cement behaved as a binder as it stabilised the silty sand, the increase in the critical shear stress with 0.6% of cement treatment would not be greater than that with 0.6% lignosulfonate treatment. It is blatant that the stabilisation mechanisms of lignosulfonate and cement on the dispersive clay are different. Cement can alter the mineralogy of the clay with its ion exchange capacity to form a stable clay structure, which is sufficiently resistant to erosion. Hence, it can be concluded that altering the clay mineralogy of dispersive clay with cement is more effective than binding the clay particles with lignosulfonate.



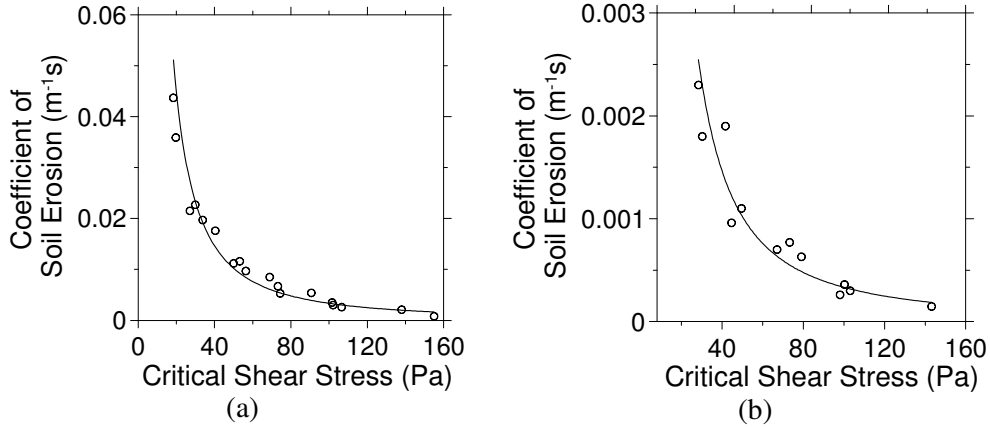
**Fig. 6. Variation of critical shear stress with the amount of (a) Lignosulfonate and (b) Cement for silty sand**



**Fig. 7. Variation of critical shear stress with the amount of (a) Lignosulfonate and (b) Cement for dispersive clay**

As shown in Fig. 6, the critical shear stress changes linearly with the stabiliser dosage of both cement and lignosulfonate for the silty sand. A similar trend was observed for lignosulfonate treated dispersive clay (Fig. 7(a)). However, the increase in the critical shear stress is not quite linear for cement treated dispersive clay (Fig. 7(b)). Figures 6 and 7 also indicate that the critical shear stress of all soils compacted to 95% is more than those compacted to 90%. In addition, the difference between the critical

shear stress of soil compacted to 95% and 90% shows a continuously increasing trend as the amount of cement and lignosulfonate increase. To determine a simple expression for estimating the erosion rate of stabilised soils, an attempt was made to develop an empirical relationship between the critical shear stress and the coefficient of soil erosion. It was found that all data points for treated silty sand fall on a best fit line following a power function as shown in Fig. 8(a). A similar trend was observed for the treated dispersive clay as illustrated in Fig. 8(b).



**Fig. 8. Variation of coefficient of soil erosion with critical shear stress for treated (a) silty sand and (b) dispersive clay**

Thus corresponding empirical expression for the erosion rate of chemically treated soils can be determined by:

$$\dot{\varepsilon} = \frac{a}{\tau_c^b} [\tau - \tau_c] \quad (6)$$

where,  $a$  and  $b$  are constant parameters. Values of  $a$  and  $b$  are 5.6 and 1.61, respectively, for treated silty sand, while they are 0.6 and 1.62 for treated dispersive clay.

Based on the results given in Fig. 6 and Fig. 7, the critical shear stress of treated soil can be calculated using:

$$\tau_c = \tau_{co} + m(CP) \quad (7)$$

where,  $\tau_{co}$  (Pa) is the critical shear stress of untreated soil; and  $m$  is the proportionality coefficients as tabulated in Table 1. Values of  $m$  for cement treated dispersive clay were calculated using estimated straight lines (dotted lines in Fig. 7(b)).

**Table 1. Values of  $m$  and critical shear stress of untreated soil**

Stabiliser type	Degree of compaction (%)	Silty sand		Dispersive clay	
		( $m$ )	( $\tau_{co}$ )	( $m$ )	( $\tau_{co}$ )
Lignosulfonate	95	217.8	6.0	151.6	14.1
	90	166.0	2.8	103.1	9.8
Cement	95	48.2	6.0	209.2	14.1
	90	35.2	2.8	145.2	9.8

## CONCLUSIONS

This paper recaps an experimental method for evaluating the critical shear stress and the coefficient of soil erosion of chemically stabilised, two erodible soils from New South Wales, Australia. It was found that these stabilisers reduced the coefficient of soil erosion and significantly increased the critical shear stress. The increase in the critical shear stress of the silty sand with only 0.6% lignosulfonate treatment was equivalent to that with around 2.5% cement treatment. However, the stabilisation of dispersive clay was more effective with 0.6% cement than 0.6% of lignosulfonate. The critical shear stress increased with an increase in degree of compaction from 90% to 95% of the maximum dry density. It was also found that the difference between the critical shear stress of 95% and 90% compacted soil increased continuously with an increase in the amount of cement and lignosulfonate. The results of this study indicated that the coefficient of soil erosion had a strong relationship with the critical shear stress following a decaying power function.

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