Erosion rate prediction of chemically treated soil using Internal Erosion Apparatus

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Abstract

Chemical stabilization is an effective ground improvement technique for controlling erosion. Two stabilizers, lignosulfonate and cement, were used to study how effectively they could stabilize erodible silty sand collected from Wombeyan Caves, NSW, Australia. To conduct this research, four dosages of cement (0.5, 1, 1.5, and 2%) and four dosages of lignosulfonate (0.1, 0.2, 0.4, and 0.6%) by dry weight of soil were selected. All treated and untreated soil specimens were compacted to 90 and 95% of their maximum dry density to study the effect of compaction level on erodibility. The erosion characteristics of treated and untreated soil samples were investigated using a process simulation apparatus for internal crack erosion designed and built at the University of Wollongong. The findings of this study indicated that both chemical stabilizers increased the resistance to erosion because of their cementing properties. It was also found that the critical shear stress increased linearly with the amount of stabilizer, and the coefficient of soil erosion decreased as a power function of the critical shear stress..

Key words: Ammonium Lignosulfonate, Cement, Erosion, Piping, Critical Shear Stress, Coefficient of Soil Erosion.

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Introduction

Internal erosion and surface erosion are two important failure modes of earth fill dams all around the world. Therefore it is very important to improve the erosion resistance of the erodible soils using appropriate cost effective techniques. Reducing the erosion rate by increasing the erosion resistance with chemical stabilisers is one of such solutions to avoid surface erosion and piping erosion in earth structures. In the past, various admixtures such as lime, cement, fly ash, milled slag, bitumen and calcium chloride have been used to stabilise erodible soils. Lime and gypsum treated soils were used at the foundation-embankment interface, on the slope surface of the embankment, at and around the rigid structures to reduce the erosion rate of dispersive soils (Biggs, 2004; Cole et al, 1977; Phillips, 1977). Cement, milled slag and fly ash were also used to reduce the erodibility of dispersive and colluvial soils (Indraratna, 1996; Indraratna et al, 1991). However, some limitations such as sulphate attack of concrete and steel structures because of gypsum treatment and problems with vegetation on the lime treated soils due to undesirable pH levels caused by the treatment (Perry, 1977; Biggs, 2004) have encouraged researchers to find alternative nontraditional stabilisers. In this study, a new stabiliser, (ammonium lignosulfonate) and a traditional stabiliser, (cement) were tested for their effectiveness in increasing the erosion resistance.

In the past, lignosulfonate stabiliser was used to improve the strength of different types of soils ranging from non-cohesive to cohesive (Tingle et al, 2003; Puppala and Hanchanloet, 1999; Pengelly, 1997; US Army Corps Engineering Manual, 1995; Karol, 2003; Shulga et al, 2001). Puppala et al (1999) reported that lignosulfonate with sulphuric acid treatment on clayey soils increased the shear strength properties (both cohesion and friction angle), resilient modulus and structural coefficients significantly. Ammonium lignosulfonate was used in conjunction with potassium chloride to reduce the swelling properties of the soils (Pengelly, 1997). Lignin based stabilisers such as ammonium persulfate-lignin, sodium bichromate-lignin etc. were applied as grouts to bind particles together especially in fine granular soils (US Army Corps Engineering Manual, 1995**;** Karol, 2003). However, these lignin grouts were unsuccessful in improving the shear strength of clayey soils due to their low penetrability. Even though sodium bichromate-lignin was successful in improving soil properties, it disappeared from the market due to heavy metal constituents in the stabiliser. Lignosulfonate based inter polymer admixtures were successfully used to reduce the erosion rate of sandy soil (Shulga et al, 2001). In addition some other researchers performed experimental studies to investigate the suitability of this particular type of chemical in low volume road construction (Chemstab, 2003; Tingle et al, 2003).

Since properties of lignin based stabilisers vary significantly with extraction process, there is no standard stabilisation mechanism for these stabilisers as defined for traditional stabiliser such as cement, lime etc. Different kinds of lignin stabilisers with different properties are available in the market and therefore, it is necessary to examine their effects on the related soil specimens before applying in the field.

Some basic terms in erosion studies are outline in Figure 1. It shows the typical linear relationship between the erosion rate and the applied hydraulic shear stress. The erosion rate is here defined as the amount of eroded soil in unit time over unit surface area. Critical shear stress is the minimum applied hydraulic shear stress necessary to initiate erosion. It will therefore be determined by extrapolating a straight line to zero erosion rate. The slope of this straight line is presumed to be the coefficient of soil erosion

Many studies have been conducted to investigate the erosion characteristics of soil in embankment dams. Wan and Fell (2004) performed a comparative study using hole erosion and slot erosion tests to investigate the progression of the erosion and breaching time. They concluded that erosion rate is highly influenced by degree of compaction and placement water content. Christensen and Das (1973) carried out hole erosion tests to study the erosion characteristics of cohesive soils. They found that erosion rates of cohesive soils depend on soil composition, surface roughness, hydraulic shear stress and temperature. Reddi et al (2000) investigated the internal and surface erosion of sand-kaolinite mix using flow pump tests and tried to estimate the seepage erosion using surface erosion parameters. They performed internal erosion tests by pumping eroding fluid through intact compacted soil, and surface erosion tests by pumping eroding fluid through a preformed 7mm diameter hole. Their research findings showed that erosion rate measured from surface erosion experiments was much greater than that of from seepage erosion tests. Sanchez et al (1983), based on triaxial crack erosion test results, reported that the effect of compaction on erosion of silty material is little whereas its effect on clayey soils is significant.

Authors have designed and built an Internal Erosion Apparatus, which can continuously monitor the erosion rate, to investigate the erosion characteristics of chemically stabilised soil.

Experimental Investigation

Properties of soil and chemical stabilisers used in the testing program

A silty sand soil collected from Wombayan caves in NSW, Australia was selected for this study as it has been classified as an erodible soil according to the standard pinhole test. The large extent of silt and find sand present in the soil makes it erodible. The particle size distribution of the soil is shown in Fig 2. The soil is non-plastic and classified as silty sand (SM) according to the unified soil classification system. The maximum dry density and the optimum moisture content obtained from the standard proctor compaction method were 1711 kg/m^3 and 10.3%.

General purpose cement manufactured in Australia and ammonium lignosulfonate were selected for the experimental investigation. The lignosulfonate mixture is completely water soluble, dark brown liquid, having a pH value of approximately 4. These stabilisers are non-corrosive to metals and non-flammable, and also they are not classified as hazardous according to NOHSC criteria (CHEMSTAB 2003).

Sample preparation

Erosion tests

Four cement dosages of 0.5%, 1%, 1.5%, and 2% and four lignosulfonate dosages of 0.1%, 0.2% 0.4%, and 0.6% by dry weight of soil were selected for the study. Different mixing procedures were adapted for both stabilisers. For cement, soil was mixed thoroughly with the pre calculated amount of cement using a soil mixer, and water was then added to achieve the optimum moisture content. However, in the case of lignosulfonate, pre calculated amount of lignosulfonate was firstly mixed with the required amount of water to obtain the optimum water content, and the mix was then added to the soil. Once the soil was mixed with stabilisers, it was then compacted statically in 5 layers in a copper mould having the dimensions of 72mm in diameter and 100mm in length. To study the effect of degree of compaction, all untreated and treated soil samples were prepared at the optimum water content and at two different relative compaction ratios, 90% and 95% of the maximum dry density. Since one of the main objectives of this research project is to investigate the effect of cohesion due to cementation on the erosion rate, the maximum dry density of untreated soil of 1711kg/m^3 and optimum water content of 10.3% were chosen as maximum dry density and optimum moisture content of all treated samples. A perfectly cylindrical hole having the diameter of 10mm was drilled through the specimen using a specially made guiding block for the drill bit (Fig 3). All untreated and treated samples were wrapped in moisture proof bags and then kept in a humidity controlled chamber for curing for seven days. In order to saturate the compacted soil samples, they were immersed in the eroding fluid (tap water) for 48 hours. A 2.5kPa normal load was applied during the saturation process. Weight of the sample was measured every 12 hours and accordingly the degree of saturation was determined. Since the soil was a silty sand, it was possible to reach more than 95% of saturation with this technique.

Erosion tests were carried out using a new Internal Erosion Apparatus (IEA) designed and built at University of Wollongong. This equipment has an adjustable tank with the capacity of 25 *l* to apply a hydraulic gradient up to 40 across the sample. The eroding fluid was stored in a 1000 *l* tank and pumped into the moving constant head tank during erosion testing. The schematic diagram and the photograph of the experimental set up are shown in Fig 4(a) and 4(b). Two pressure transducers were connected at both ends of the sample to measure the pressure difference across the crack. To measure the erosion rate continuously with time, an inline process turbidity meter having an overall span of 0-3500 NTU was connected next to the downstream side of the soil sample for monitoring the effluent turbidity continuously during the erosion process. The turbidity values were then used to calculate the rate of erosion using the relationship developed by the authors between the concentration of solids (kg/m^3) and the turbidity (NTU) for the selected soil. In order to measure the flow rate continuously, weight of the effluent was measured with an electronic balance. As shown in Figures 4(a), all pressure transducers, turbidity meter and electronic balance were connected to a data acquisition system (data taker).

Scanning Electron Microscopy (SEM)

To explain the stabilisation mechanisms for both chemical additives, the SEM tests for untreated and chemically treated soils were conducted. For every sample, the soil was compacted to its 95% of maximum dry density at the optimum moisture content of 10.3%. A cylindrical sample, having the size of 18mm in diameter and 10mm in height, was prepared for the tests. Prepared samples were then kept in a humidity controlled chamber for curing for seven days.

Interpretation of observations

When the soil pipe diameter changes by $\delta\phi_t$ in δt time, the amount of soil eroded during this time period will be:

$$\delta m = \frac{\pi \phi_t l \rho_d}{2} \times \delta\phi_t \tag{1}$$

where, δm is the amount of soil eroded during a selected time interval δt (kg); ρ_d is the dry density of compacted soil (kg/m^3); l is the length of the soil pipe (m); ϕ_t is the diameter of the soil pipe at time t (m); and $\delta\phi_t$ is the diameter change in (m) δt time.

Based on the experimental observations, the amount of soil eroded in a selected time interval δt will be:

$$\delta m = kQT \times \delta t \tag{2}$$

where, Q is the average flow rate (m^3/s) through the soil pipe at time interval δt; T is the average turbidity (NTU) of the effluent at the time interval δt; and k is the empirical factor relating turbidity to the soil solids concentration in the flow. Measured k value, determined based on a linear relationship between the concentration and the turbidity, for untreated and cement treated soils was 0.013 kg/m^3/NTU. A slight smaller k value (0.011 kg/m^3/NTU) was obtained for lignin treated soils.

Combining eqs. (1) and (2) yields:

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

Equation (3) can be used to calculate the change in diameter of the soil pipe during erosion process for every 3 sec time interval by using the flow rate, turbidity of effluent and the initial diameter of the soil pipe. The average erosion rate during the time interval δt can be calculated using equation (4), and it will then be used to calculate the erosion rate at time t.

$$\dot{\varepsilon} = \frac{kQT}{\pi \phi_t l} \tag{4}$$

where, $\dot{\varepsilon}$ is the average erosion rate during the time interval δt (kg/s/m^2).

The applied hydraulic shear stress τ on the soil pipe surface can then be calculated from:

$$\tau = \frac{\rho_w g h \phi_t}{4} \tag{5}$$

where, ρ_w is the density of the eroding fluid (kg/m^3); g is the gravitational acceleration (m/s^2); and h is the applied hydraulic gradient across soil pipe at time t.

Results and Discussion

A number of erosion tests have been performed on both untreated and chemically stabilised soil samples and the results obtained from the investigation are discussed here. Fig 5 shows the example for the eroded soil surface after the erosion test for the 0.2% lignin treated soil compacted to its 95% of maximum dry density at the optimum moisture content of 10.3%. Figures 6(a), 6(b) and 6(c) show the variation of hydraulic shear stress, erosion rate and soil pipe diameter change with time, respectively, calculated on the basis of results obtained from the Internal Erosion Apparatus for 0.4% lignosulfonate treated soil at 95% of maximum dry density. A similar pattern was observed for all other erosion tests conducted for treated and untreated soil samples. As erosion progresses, after a certain time, hydraulic gradient starts dropping due to the enlargement of the soil pipe, which ultimately reduces the applied hydraulic shear stress on the soil surface (Fig. 6a). Its effect on the erosion rate is demonstrated in Fig. 6(b). After the erosion rate reaches the peak, its value gradually decreases with time. In order to illustrate this clearly, the erosion rate against the hydraulic shear stress is plotted in Fig 7. At the beginning of the erosion process, the erosion rate increases linearly with the increasing hydraulic shear stress, which follows the typical erosional behaviour observed by several researchers in the past (Arulananthan et al, 1975; Sargunan, 1977; Shaikh et al, 1988; Reddi et al, 2000; among others). As the erosion process continues, the erosion rate decreases due to the reduction in hydraulic shear stress, whereby the all data points fall on a best fit line as shown in Fig. 7. The critical shear stress and the coefficient of soil erosion for 0.4% lignosulfonate treated soil (compacted at the optimum water content of 10.3% and 95% of the maximum dry density) were 90.7 Pa and 0.0054, respectively.

Effect of stabiliser dosage and compacted density on Critical Shear Stress and Coefficient of Soil Erosion

In order to gain a clear understanding of the effect of lignosulfonate and cement stabilisation on the coefficient of soil erosion and the critical shear stress, the erosion rate against the hydraulic shear stress for all untreated soil and treated soil are plotted in the same graph. Fig 8 and 9 plot the variation of erosion rate with the hydraulic shear stress for the two chemical stabilisers (compacted at 95% relative density). It is evident that these relationships are linear and the slope of the lines represents the coefficient of soil erosion. At 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 soil is non-cohesive, and all untreated and treated 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 the increase in the erosion resistance of the treated soil in contrast to the untreated soil was the enhancement of cohesion attributed to cementation. The stabilisation mechanism for both chemical additives is described in the next section.

In order to obtain a clear picture about the stabilisation mechanisms of both stabilisers, digital images were captured using the Scanning Electron Microscope (SEM). Figs. 10, 11 and 12 show the morphology of the untreated, 2% cement treated and 0.4% lignosulfonate treated soil, respectively. As can be seen from Fig 10, untreated soil grains are distinctly separate with clear boundaries between them. However, it is evident from Fig 11 that particles are bonded with precipitated cementing (bonding) materials. In the case of lignosulfonate treatment, the particles are coated with the lignosulfonate, and these coated grains are also bonded together closely to produce a stronger soil structure as shown in Fig 12. It could be concluded based on the observations from SEM photographs that both stabilisers act like cementing agents to bind the soil particles together to form an erosion resistant soil surface.

When the cement dosage is increased to 2%, the critical shear stress increases from 6 Pa to 101.6 Pa, and the coefficient of soil erosion decreases by 50 times that of the untreated soil. A similar response was observed for lignosulfonate treated soil. However, it is interesting to note that the coefficient of soil erosion drops from 0.181 to 0.0021 even with the addition of 0.6% of lignosulfonate. Moreover, the increment in the critical shear stress with 0.6% of lignosulfonate treatment is higher than that of 2% of cement stabilised soil.

All of the specimens compacted at the 90% of the maximum dry density show the same trend as the 95% compacted specimens. In order to illustrate the effect of compaction on the critical shear stress and the coefficient of soil erosion, they were plotted against the stabiliser dosage in Figures 13 and 14. These plots show that the critical shear stress changes linearly with the stabiliser dosage of both cement and lignosulfonate. It can be seen from these two figures that the critical shear stress of all the 95% compacted soil is more than that of the 90% compacted soil. In addition, it is interesting to note that the difference between the critical shear stress of 95% and 90% compacted soil shows a continuously increasing trend as the amounts of cement and lignosulfonate dosages increase. As expected, the degree of inter particle bonds in 90% compacted state is less than that in the 95% compacted state because of the closer packing of the latter.

To determine a simple expression for estimating the erosion rate of stabilised soil, 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 the untreated and treated soil fall on a best fit line of power function as plotted in Figure 15.

The final expressions for the erosion rate for chemically treated soils is determined empirically as:

$$\dot{\varepsilon} = \frac{\alpha}{\tau_c^{\beta}}\left[\tau - \tau_c\right] \tag{6}$$

where, α =1.5 and $\beta \approx 1.3$; $\dot{\varepsilon}$ is the erosion rate (kg/s/m^2); τ is the applied hydraulic shear stress (Pa); τ_c is the critical shear stress (Pa).

and

$$\tau_c = \tau_{c0} + \delta(CP) \tag{7}$$

where, τ_{c0} is the critical shear stress of untreated soil (Pa); δ is the proportionality coefficient as tabulated in Table 2; and *CP* is the amount of chemical additives (%).

If the critical shear stress of the untreated soil is known, expressions (6) and (7) can be used to estimate the erosion rate and the critical shear stress of the treated soil, respectively.

Conclusions

This paper summarises an experimental method to evaluate the critical shear stress and the coefficient of soil erosion of chemically stabilised erodible soil collected from Wombayan Caves, NSW, Australia. An Internal Erosion Apparatus was designed and built to conduct erosion tests to study the effectiveness of chemically treated soils, using two additives, namely, cement and ammonium lignosulfonate. Based on the experimental results, it was found that both stabilisers were successful in reducing the coefficient of soil erosion and increasing the critical shear stress significantly. It was also observed that, a considerably smaller amount of lignosulfonate compared to cement was sufficient to achieve a given increase in the erosion resistance. The results of this study indicated that the coefficient of soil erosion has a definite relationship with the critical shear stress following a decaying power function. Furthermore, the critical shear stress increases with the increase in degree of compaction from the 90% to 95% of maximum dry density. It was also found that the difference between the critical shear stress of 95% and 90% compacted soil increased continuously with the increase in the amounts of cement and lignosulfonate. In addition, an empirical expression has been developed to evaluate the erosion rate of chemically stabilised soil in terms of the amount of chemical agent added and the magnitude of critical shear stress of the untreated soil.

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Figures and Tables

Table. 1. Proportionality Coefficient to determine Erosion Rate

Stabiliser Type	Degree of Compaction	Proportionality Coefficient(δ)	Critical Shear Stress of untreated soil(τ_{c0})
Cement	95%	46.8	6.0
	90%	36.1	2.8
Lignin	95%	217.8	6.0
	90%	166.0	2.8

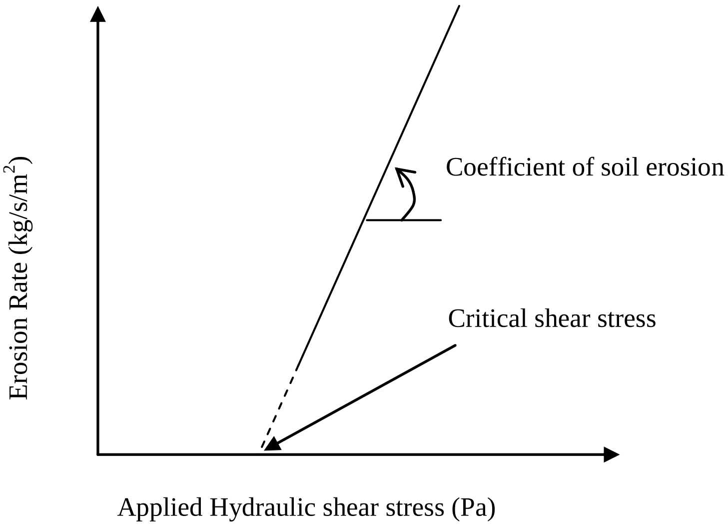


Fig. 1. Typical curve for erosion rate vs. applied hydraulic shear stress

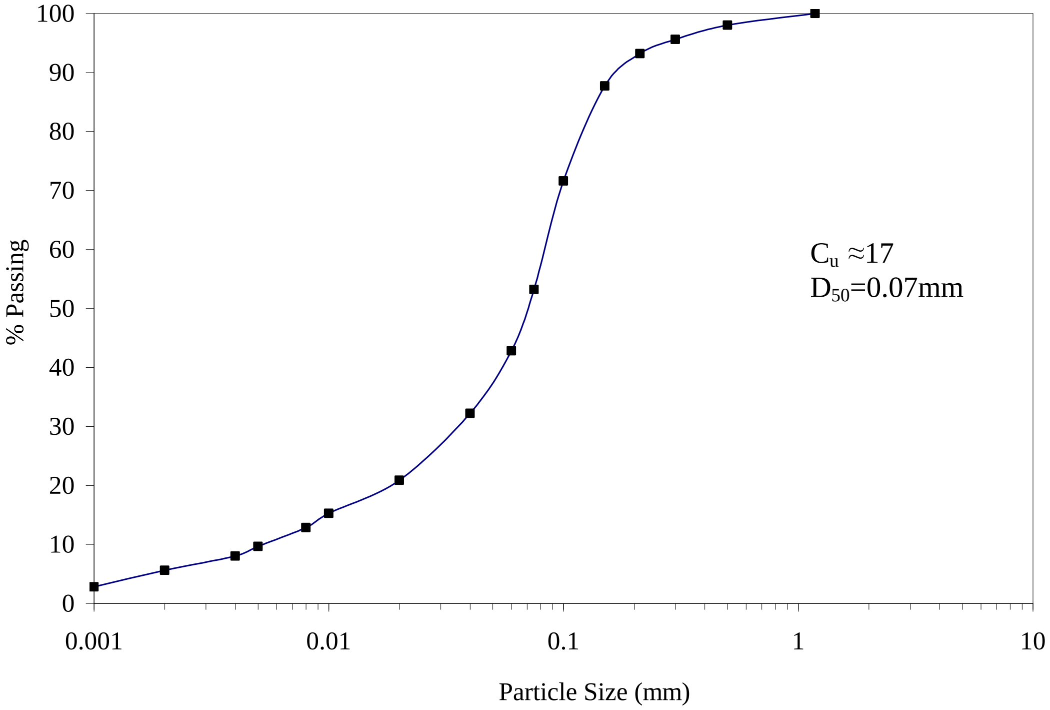
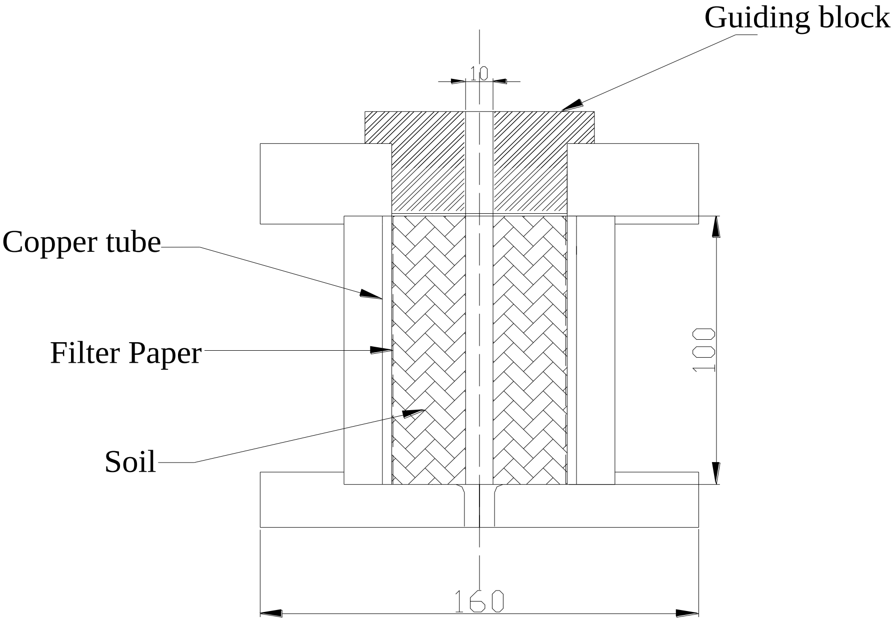


Fig. 2. Particle size distribution of Wombayan caves soil



* All dimensions are in millimeters.

Fig. 3. Compaction mould and soil pipe forming setup

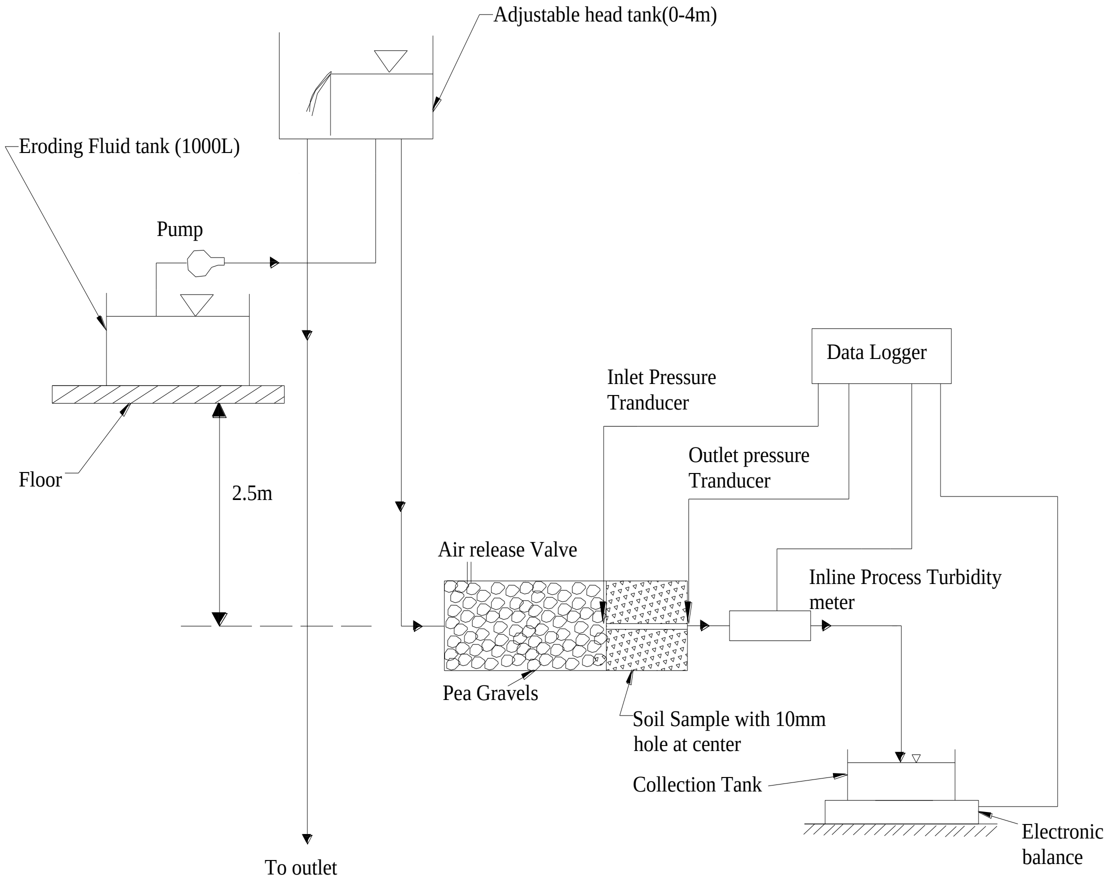


Fig. 4a. Schematic diagram of Internal Erosion Apparatus (IEA)

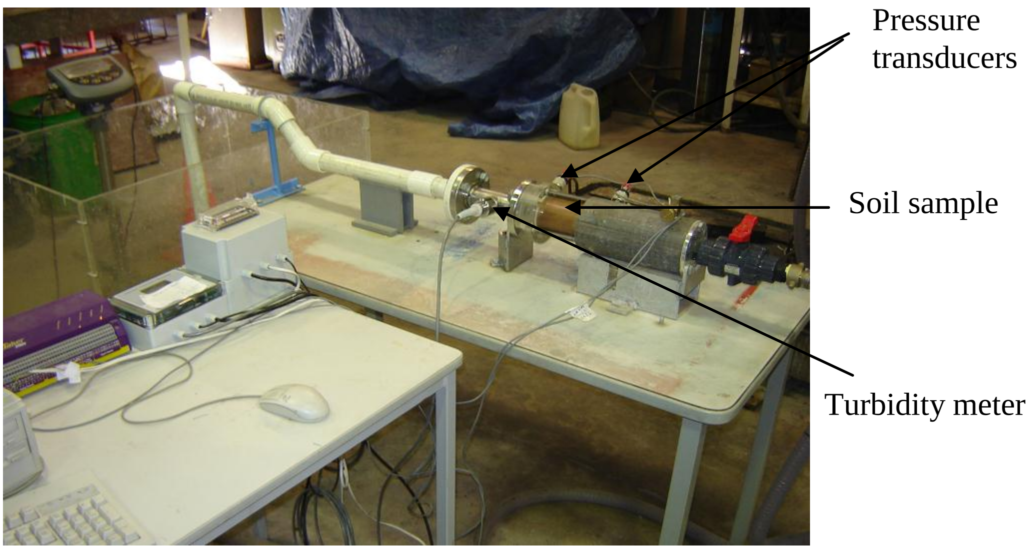


Fig. 4b. Photograph of the Internal Erosion Apparatus (IEA)

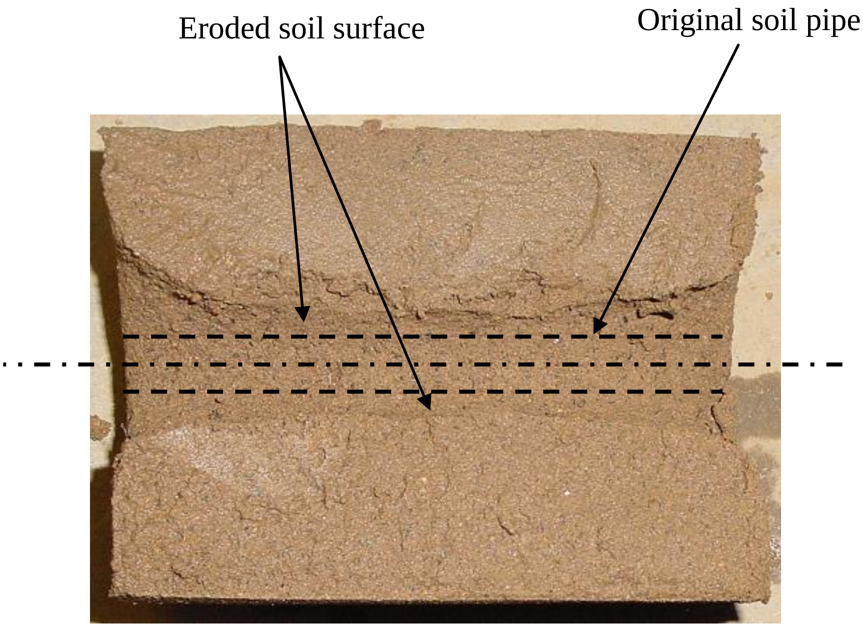


Fig. 5. Eroded soil surface for 0.2% lignin treated soil compacted at the optimum moisture content and the 95% of maximum dry density

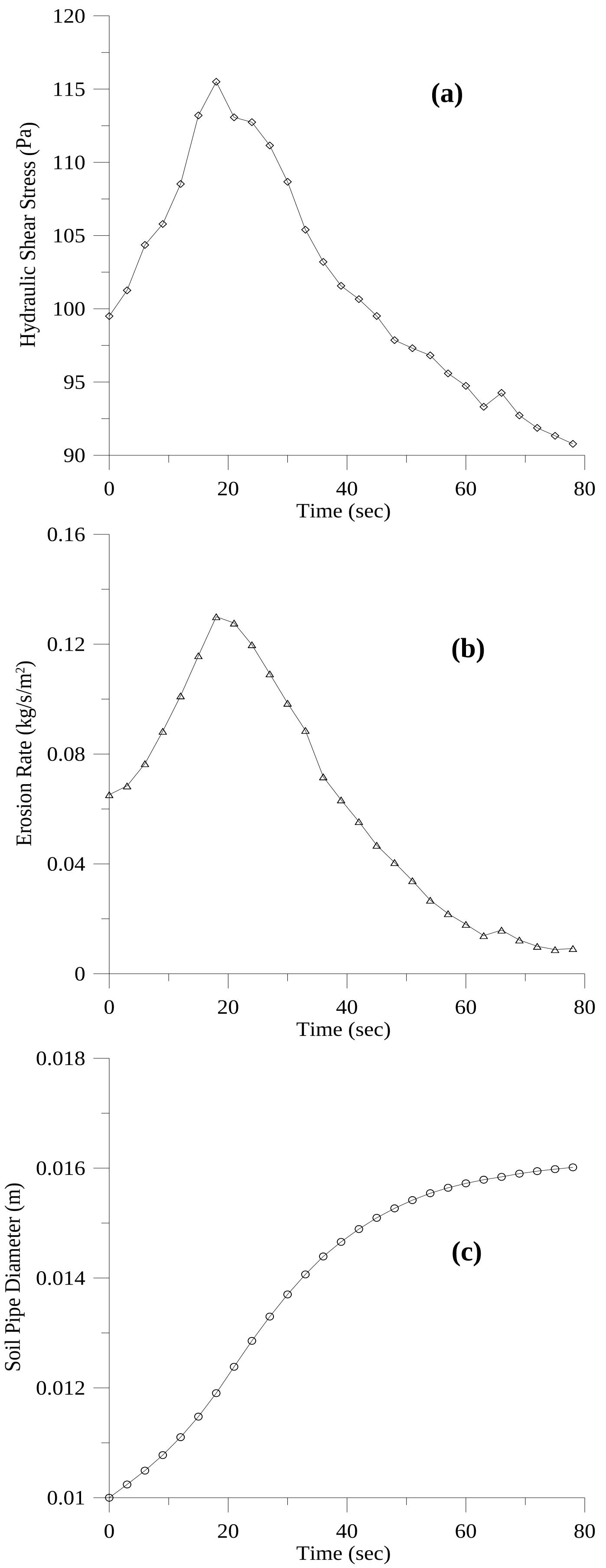


Fig: 6 Variation of (a) hydraulic shear stress, (b) erosion rate, and (c) soil pipe diameter with time for 0.4% lignosulfonate treated soils at 95% relative compaction

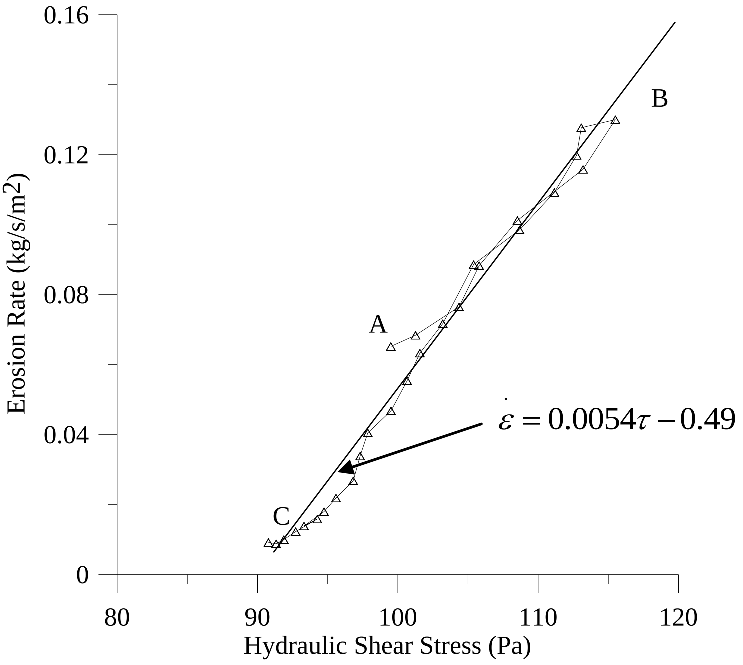


Fig. 7. Erosion rate vs. Hydraulic shear stress for 0.4% lignosulfonate treated soils at 95% relative compaction

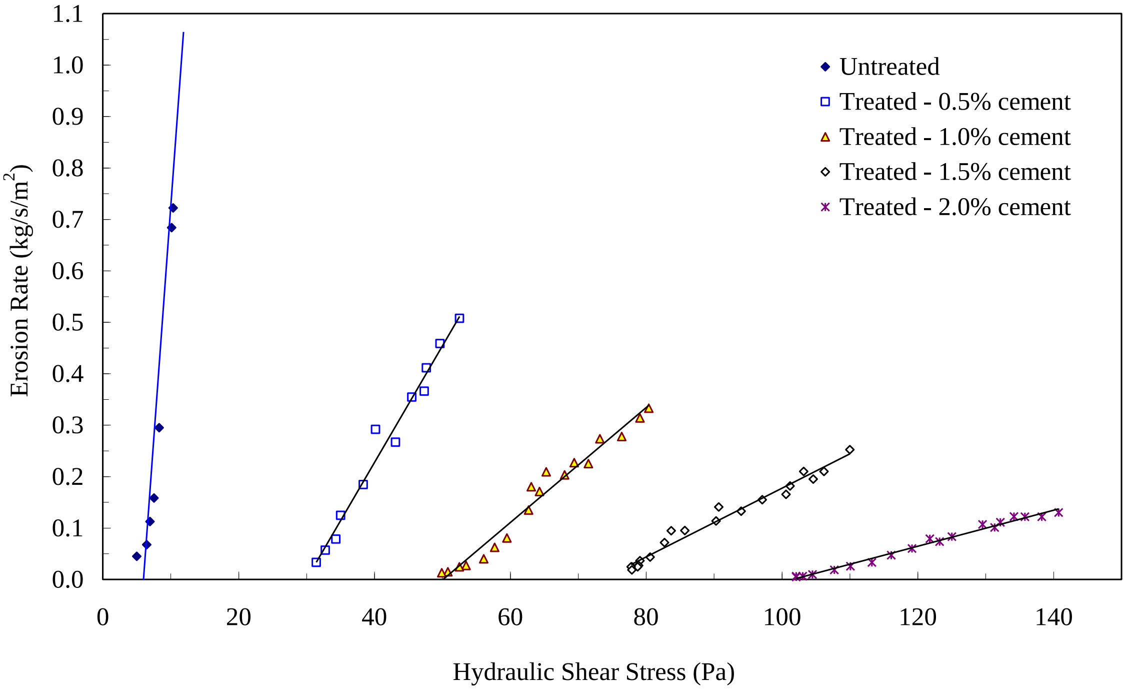


Fig. 8. Erosion rate against hydraulic shear stress for untreated and cement treated soil compacted at optimum and 95% of maximum dry density

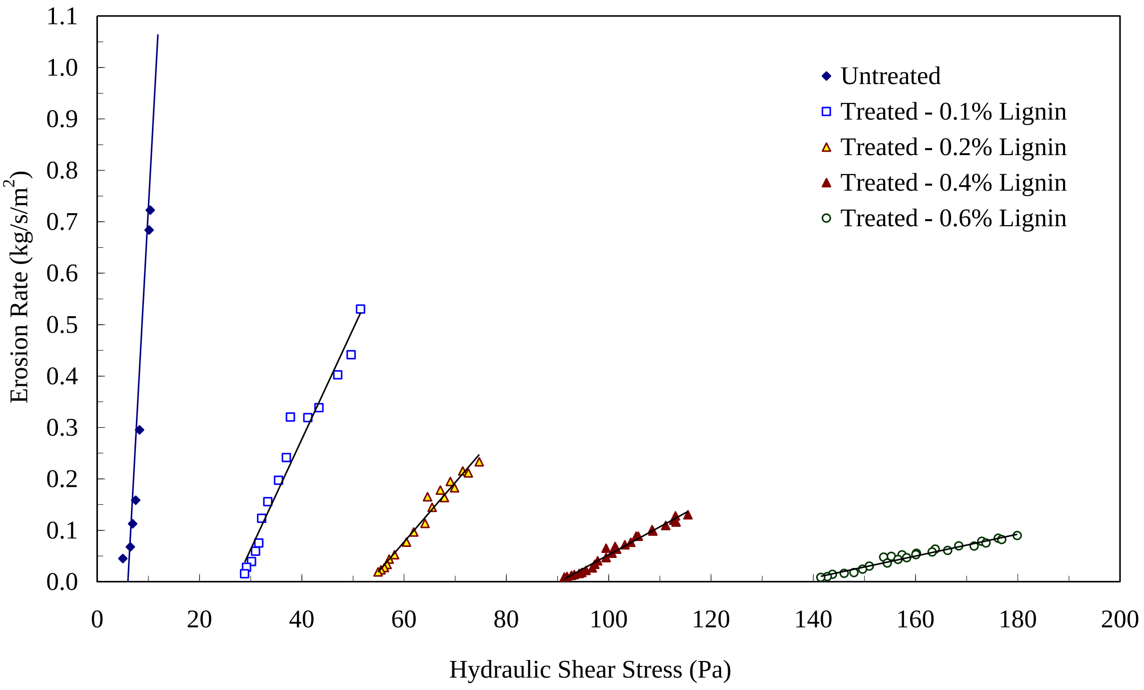


Fig. 9. Erosion rate against hydraulic shear stress for lignosulfonate treated soils compacted at optimum and 95% of maximum dry density

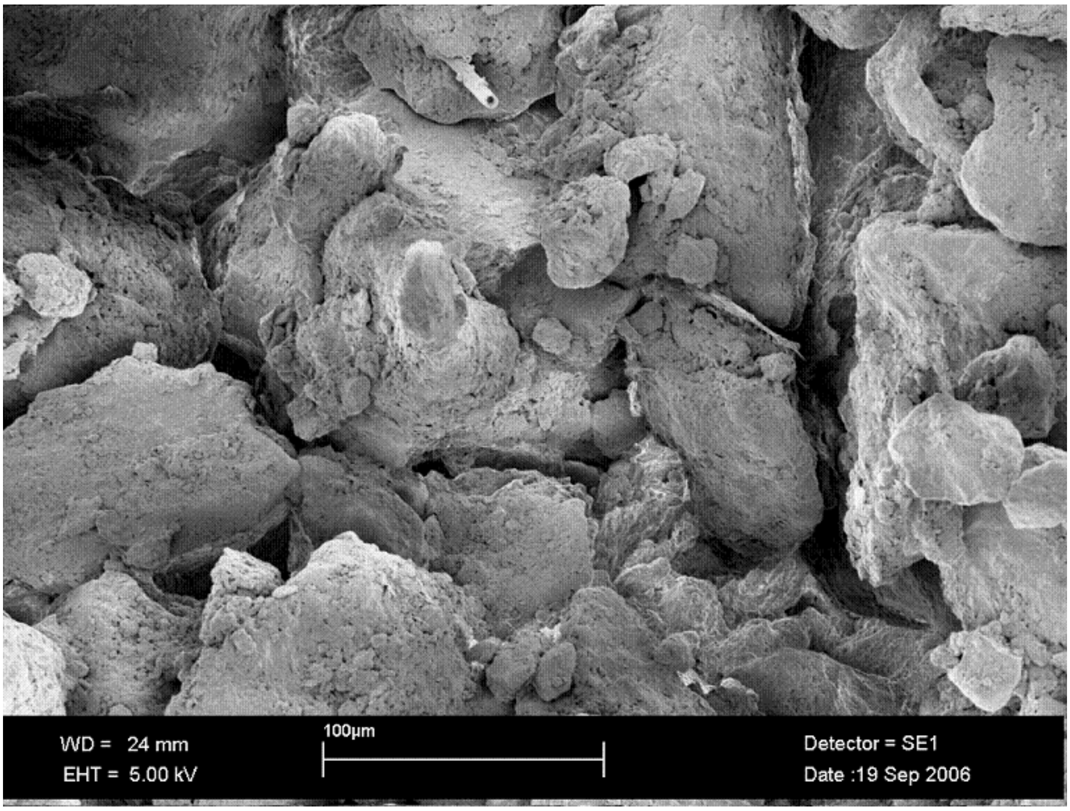


Fig. 10. Micro features of untreated silty sand

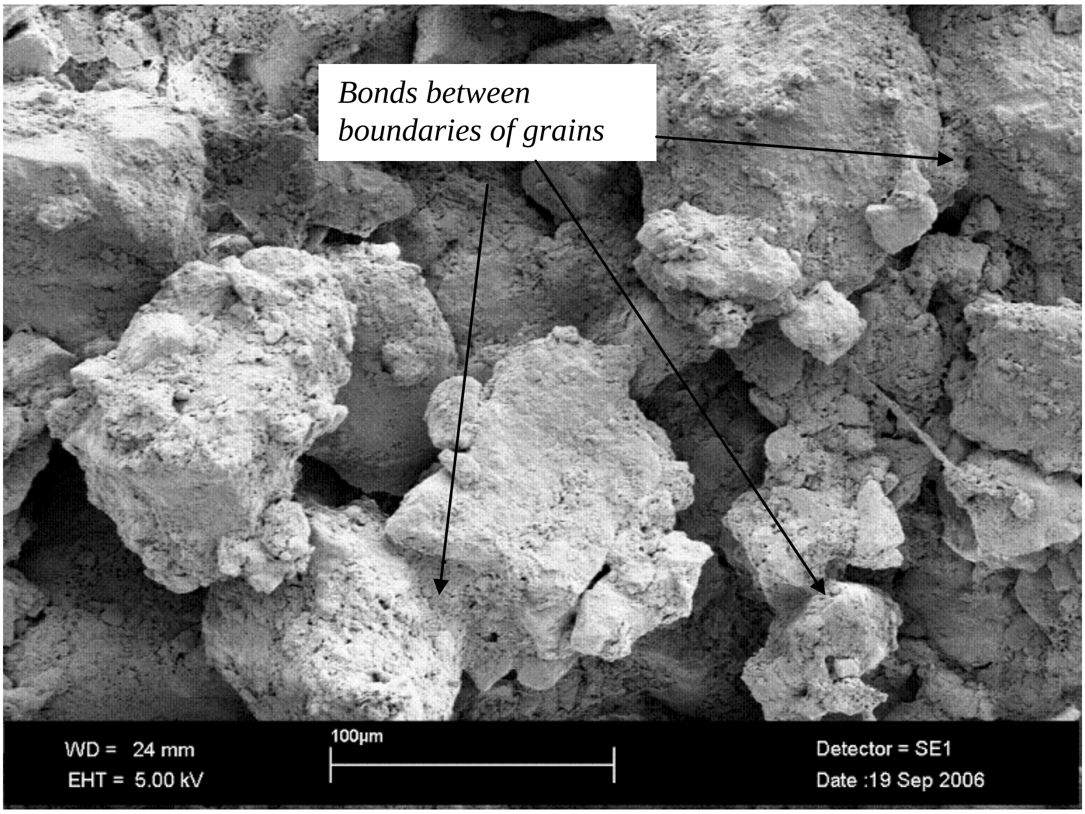


Fig. 11. Micro features of 2% cement treated silty sand

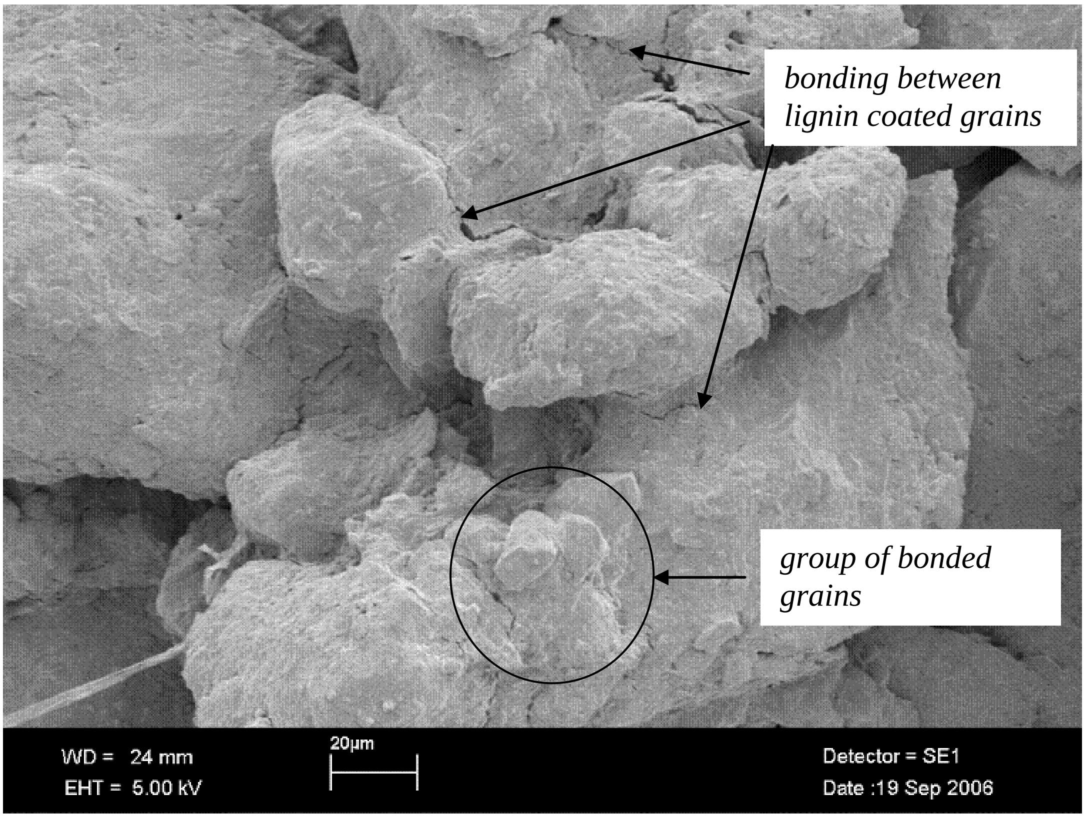


Fig. 12. Micro features of 0.4% lignosulfonate treated silty sand

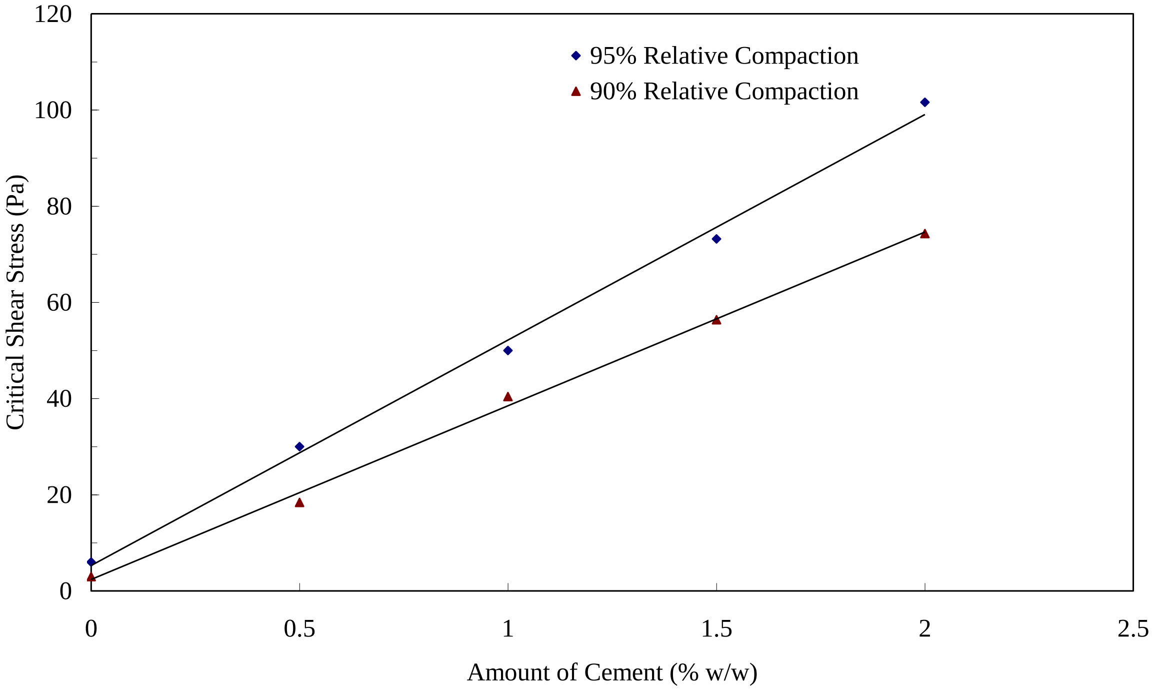


Fig. 13. Variation of critical shear stress with cement quantity

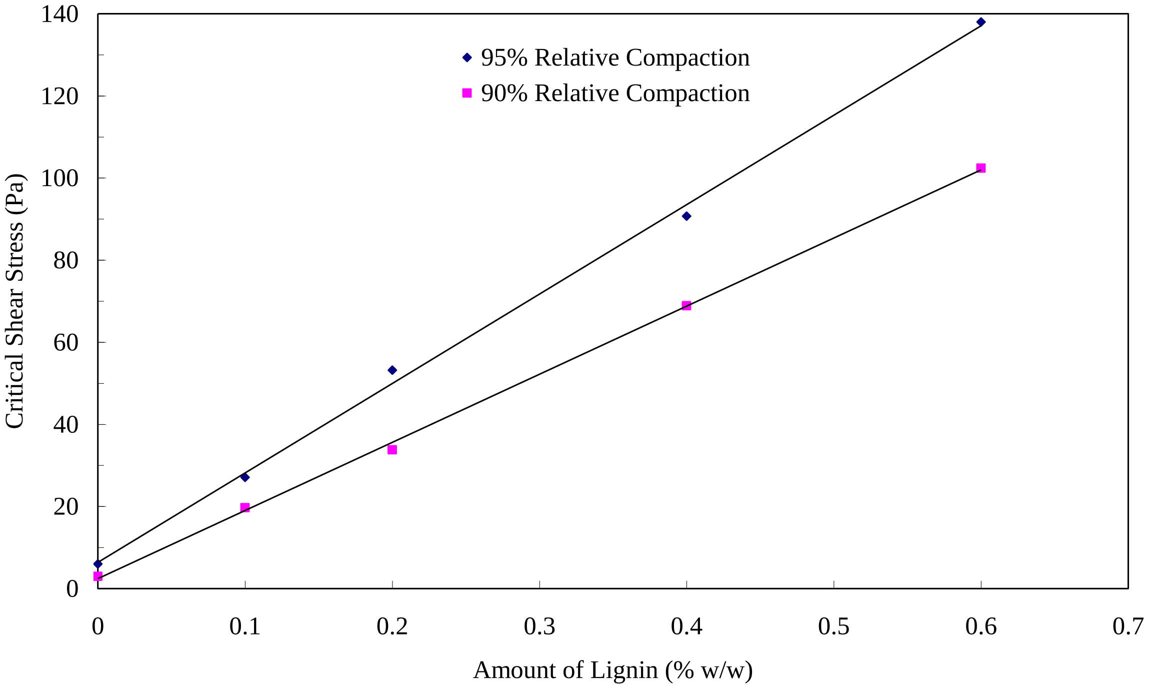


Fig. 14. Variation of critical shear stress with lignosulfonate quantity

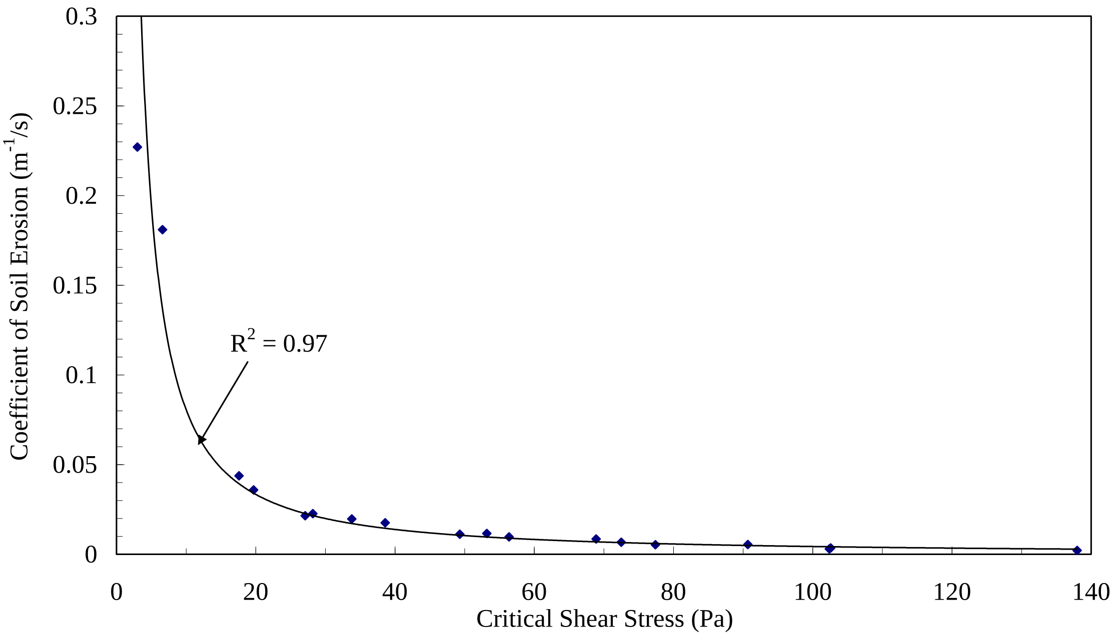


Fig. 15. Variation of coefficient of erosion with critical hydraulic shear stress for all cement and lignosulfonate treated soil