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compressive strength of the soil increased in excess of 100% with electrokinetic treatment alone while the lime-enhanced electrokinetic treatment led to an almost 200% strength increase. The liquid limit and plastic limit increased causing the plasticity index to decrease, indicating increases in soil compressive strength and workability. These results suggest the potential of developing this technique to improve physical properties of salt affected soils effectively and efficiently, in particular in the remediation of salt affected land for infrastructure management and development.

# Modification of the Properties of Salt Affected Soils Using Electrochemical Treatments

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# Modification of the Properties of Salt Affected Soils Using Electrochemical Treatments

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## **Abstract**

In this project, an in-situ soil treatment technique using electrokinetics was tested using laboratory experimental models in order to identify the potential of this approach to modify and reinstate the physical properties of salt affected soils. Experiments were conducted in the laboratory using saline-sodic soils collected from two salt affected regions in central Victoria, Australia. Soil specimens were placed in glass tanks to represent in-situ density and in-situ water content. Using steel electrodes inserted into the soil, a direct current was passed across the soil under a constant potential gradient of 0.5 V/cm for a period of 14 days. Distilled water and a saturated lime solution were introduced to the soil via the anode electrode throughout the experimental duration. From the results it was observed that the soil dispersion, otherwise known as soil sodicity (measured as ESP -Exchangeable Sodium Percentage and SAR -Sodium Absorption Ratio) significantly decreased by up to 90% in most regions across the soil between the electrodes. The compressive strength of the soil increased in excess of 100% with electrokinetic treatment alone while the lime-enhanced electrokinetic treatment led to an almost 200% strength increase. The liquid limit and plastic limit increased causing the plasticity index to decrease, indicating increases in soil compressive strength and workability. These results suggest the potential of developing this technique to improve physical properties of salt affected soils effectively and efficiently, in particular in the remediation of salt affected land for infrastructure management and development.

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## 1. Introduction

Soil salinisation and resulting saline-sodic soil condition is known as a significant form of land degradation in many parts of the world, in particular in the arid and semi-arid regions. In Australia, soil salinity is identified as the major form of land degradation and the greatest environmental threat (Salt Force 1998) and as reported by (CSIRO 2003), the problem is ever increasing. The removal of deep-rooted native trees, grasses and vegetation causes the water table rise that brings excess amount of salt to the surface that is otherwise stored at depth.

Salinity refers to the total concentration of all soluble salts in the soil, which are typically chlorides, sulfates or carbonates of sodium, calcium and magnesium with the most common being sodium chloride (NaCl). The common parameter used to characterise the degree of salinity is the electrical conductivity (in mS/cm) of a saturated soil extract ( $EC_e$ ). The electrical conductivity measured using the 1:5 soil water suspension method,  $EC_{1:5}$  (which is a more convenient and a quicker method) can be converted to  $EC_e$  using established correlations depending on the soil textural classification as proposed by (Slavich and Petterson 1993). An  $EC_e$  greater than 16 is considered extremely saline.

Sodicity represents the amount of exchangeable sodium ions ( $Na^+$ ) in the soil compared to other exchangeable cations, predominantly being calcium ( $Ca^{2+}$ ), magnesium ( $Mg^{2+}$ ), potassium ( $K^+$ ), hydrogen ( $H^+$ ) and aluminium ( $Al^{3+}$ ). Sodicity is generally measured by ESP (exchangeable sodium percentage) while SAR (sodium absorption ratio) has also been quoted as a good indicator of the degree of sodicity (Halliwell et al. 2001; van de Graaff and Patterson 2001). SAR is the relative proportion of dissolved sodium in the pore solution compared to the sum of other dissolved cations; generally calcium and magnesium. The ESP and SAR are related by the Gapon equation (Equation 1), which governs the equilibrium between cations and other counter-ions balancing the negative charge on the clay surface.

$$\frac{Na_c}{Ca_c + Mg_c} = k \frac{[Na]}{\sqrt{[Ca] + [Mg]}} \quad (1)$$

where  $Me_c$  is metal ion on clay surface,

$[Me]$  is metal ion in pore solution and

$k$  is the Gapon exchange coefficient.

Traditionally, an ESP between 6 and 14 is considered to be sodic while an ESP greater than 15 characterise soil as strongly sodic. According to van de Graaff & Patterson, 2001, ESP more than 6 is considered sodic. The US salinity laboratory considered ESP greater than 15 to be sodic (Halliwell, et al., 2001).

The interaction between dissolved salts (including exchangeable sodium ions) in the soil solution and the exchange phase (diffuse double layer, DDL) of the clay minerals leads to variations in the clay structure and clay mineral behaviour. Such variations in the clay structure can cause poor water infiltration, permeability deterioration, surface crusting, erosion, water logging and soil strength reduction posing significant threats not only for agricultural productivity but also for the long term satisfactory performance of built infrastructure.

Current technologies to deal with salinity rely greatly upon pumping or collection of saline water, concentrating it and extracting the salt by evaporation, or simply disposing of it in a lake or to the ocean. It is known that practices such as pumping out of saline water can lead to some severe geotechnical consequences such as soil collapsing, long term sub soil consolidation processes and adverse effects on hydrologic balance of the area. The mixing of surface soil with lime is a common treatment method of saline-sodic soils. However, the practicability of lime mixing is limited only to a thin layer of the surface soil and therefore can be costly and less effective. In some localised situations, excavation of contaminated soil and disposal either on site or off site is also reported while abandoning of contaminated land is also not uncommon. In general, many of

these conventional soil remediation methods are costly, time consuming and less effective (Reddy and Shirani 1997).

At present, in Australia, the only feasible strategy to combat the detrimental effects of salinity on infrastructure appears to be living with and adapting to salinity by using of higher grade construction materials and more extensive construction practices (McRobert et al. 2003).

## 2. Electrokinetic soil treatment

The principles of electrokinetics involve applying a direct current to the soil via electrodes inserted in the soil. When a direct current is applied to a soil-liquid medium, water in the immediate vicinity of the electrodes is electrolysed and oxidation occurs at the anode, generating an acid front while reduction takes place at the cathode producing a base front. These electrolysis reactions are,



and cause the pH to decrease at the anode and increase at the cathode. The development of this pH gradient (acid/base profile) and its effects on the species transport through soil porous medium have been investigated in detail and well documented by many researchers (Acar and Alshawabkeh 1993; Acar et al. 1990; Eykholt and Daniel 1994; Jayasekera 2004; West and Stewart 1995).

The passing of an electric current causes charged species present in the soil solution to migrate towards an oppositely charged electrode. The transportation of charged species across the soil involves several mechanisms such as electroosmosis (migration of water through the capillary

network of soil particles under the influence of an electric field), electromigration (transport of charged chemical species under an electrical gradient) and electrophoresis (movement of charged particles under an electric field). The migrated species can then be removed by one of several different methods such as electroplating, adsorption onto the electrode, precipitation and co-precipitation at the electrode or pumping near the electrode (Pamukcu et al. 1997). The combined effects of these complex electro-chemical processes alter the physico-chemical properties of the soil.

There are reported instances extending back to the 1930's, about the use of electrokinetics to improve engineering characteristics of soil, for example to dewater and stabilize, to expedite the process of consolidation and to improve the shear strength (Casagrande 1951). Some of the subsequent documented evidences include, improving stability of excavations (Chappell and Burton 1975); backfill strengthening and slope stabilization (Chappell and Huggins 1998), acceleration of consolidation (Bergado et al. 2000; Ewers et al. 2002; Johnston and Butterfield 1977), improvement of physical properties of an expansive soil (Abdullah and Al-Abadi 2005) and the treatment of dispersive soils (Jayasekera and Hall 2005; Jayasekera et al. 2004; Sadrekarimi 2005; Sadrekarimi and Sadrekarimi 2003).

After gaining a widespread interest in recent years as an in situ soil remediation and stabilisation technique, electrokinetics has also been investigated for their potential application to remove various contaminants from soils. Several laboratory experiments and some field scale pilot studies have demonstrated promising removal efficiencies of various chemical species from clay soils (Acar and Alshawabkeh 1996; Acar et al. 1994; Hamed et al. 1991; Lageman 1993; Lageman et al. 1990; Pamukcu and Wittle 1992; Reddy and Saichek 2004; Reddy and Shirani 1997; Shariatmadari et al. 2001). More recent studies have proved the versatility and effectiveness of this technique in practice as a viable in-situ soil remediation and treatment method. However, majority of these studies are focused on removal of heavy metals such as arsenic, zinc, lead, copper etc. This may be due to the greater understanding of their toxicological importance in

ecosystems and for human health, and their readily response to the technique. Limited number of studies has suggested the potential of this technique to treat saline-sodic soils with a promising degree of success. These investigations include the field scale desalinisation work by J.P. Collopy in 1958 and more recent laboratory studies on dispersive (sodic) soils by Jayasekera and Hall (2005); Jayasekera et al. (2004); Sadrekarimi (2005); Sadrekarimi and Sadrekarimi (2003) and soils contaminated with salts or salt ions (Pamukcu 1997; Pamukcu et al. 1997). However, only very limited studies have appraised the effects of electrokinetic treatments on the engineering properties of the treated soils, the information that would be of particular interest in the improvement of salt affected lands for infrastructure development or in mitigating the effect of salinity on existing infrastructure.

The purpose of this paper is to report and discuss the removal efficiency of sodium ions from two salt affected soil types with and without introduction of lime via the anode and then to discuss the effects of electrochemical processing on the soil physical properties of dispersivity (sodicity), unconfined compressive strength and consistency limits.

### **3. Materials and methods**

#### **3.1 EXPERIMENTAL SOIL**

Experiments were carried out on salt affected soils excavated and transported to the lab from two areas identified as affected by soil salinity and sodicity, in the central Victoria, Australia. The original physical and chemical properties of these soils were initially evaluated and were used as the datum for comparison of the results following the electrokinetic processing. The original properties of the test soils are summarised in Table 1.

**Table 1:** Properties of experimental soil

<b>Characteristic</b>	<b>Soil S1</b>	<b>Soil S2</b>
Clay content %	8	41
Unified Soil Classification	ML	CH
Textural Classification	Silt loam	Heavy clay
Consistency Limits (%)		
LL (Liquid Limit)	30	72
PL (Plastic Limit)	23	34
PI (Plasticity Index)	7	38
In-situ water content %	25	52
In-situ density (kg/m <sup>3</sup> )	1500	1650
Compressive strength (kN/m <sup>2</sup> )	38	97
Electrical Conductivity EC <sub>1.5</sub> (mS/cm)	2	3
Electrical Conductivity EC <sub>e</sub> (mS/cm)*	19	21
pH	4.5	4.5
Soil Dispersion (Sodicity)		
ESP (Exchangeable Sodium Percentage)	34	31
SAR (Sodium Absorption Ratio)	8	9
Degree of salinity	Extreme	Extreme
Degree of sodicity	Strong	Strong

\* EC<sub>1.5</sub> converted to EC<sub>e</sub> using the method proposed by (Slavich and Petterson 1993), based on soil textural classification

### 3.2 EXPERIMENTAL SETUP

The laboratory experiments of electrochemical treatment of contaminated soil samples were carried out using the electrokinetic test methods developed at the University of Ballarat (Jayasekera et al. 2004). The tests were conducted in glass tanks of 90 cm by 35 cm plan area. A layer of soil was placed in the tank to represent field (in-situ) density and moisture content such that the compacted thickness of soil layer is 12.5cm. Two mild steel tubes (25mm diameter, hollow, with holes drilled through the walls of the tube to allow the liquids to move freely) were placed 70 cm apart at both ends of the tank to serve as electrodes. Soil samples were supplied with a continuous flow of distilled water and saturated lime solution (CaO dissolved in distilled

water) via the hollow core anode from external reservoirs. The soil samples were subjected to a direct current (d.c.) with a constant voltage gradient of 0.5 V/cm for a period of 14 days.

After the electrokinetic processing period (14 days), the soil between the electrodes were divided in to five sections having average normalized distances of 0.1, 0.3, 0.5, 0.7 and 0.9 from the anode and were tested for their physical and chemical properties.

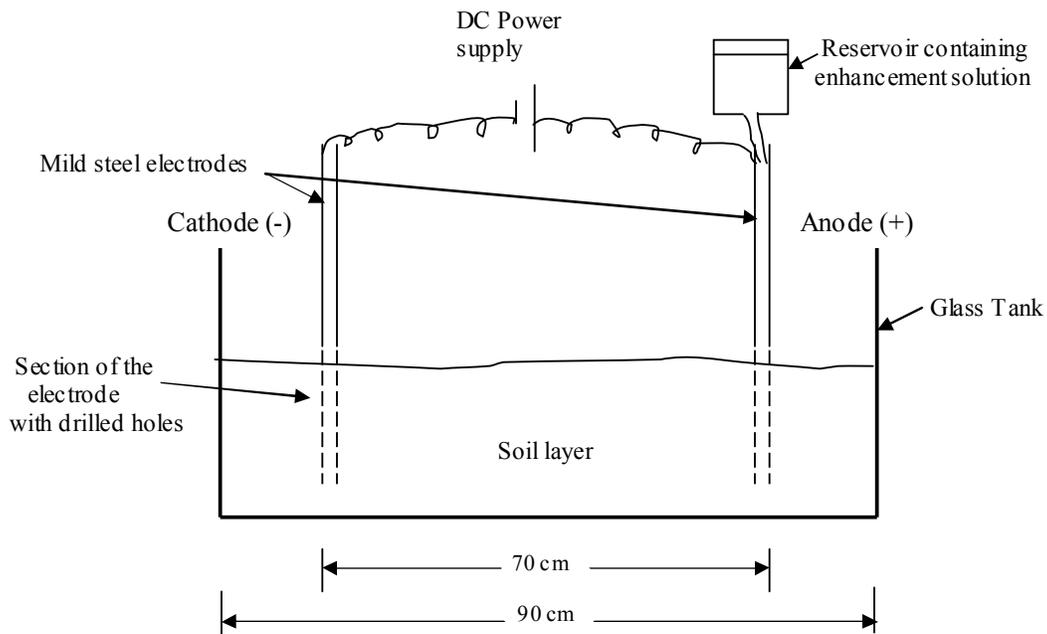


Figure 1. Schematic of the laboratory set up for electrokinetic treatment of saline soil

### 3.3 EXPERIMENTAL METHODS

Penetration tests were conducted to determine the compressive strength of the soil. The penetration tests were carried out using a GEOTESTER pocket penetrometer. Penetration readings were taken at least at three points (laterally) at each test location.

All other tests on electrokinetically treated soil were conducted on representative specimens prepared after drying and homogeneously mixing the entire soil volume collected from each section at the given distance from anode.

Electrical conductivity ( $EC_{1:5}$ ) and pH were analysed using the 1:5 soil: water suspension method (Slavich and Petterson 1993). Ionic concentrations of Na, Ca and K, were estimated using flame photo spectrometry and Mg using atomic absorption spectrometry. Sodium Absorption Ratio (SAR) was computed using the Gapon equation (Equation 1). The cation exchange capacity (CEC) was estimated using the ammonium acetate CEC analysis technique at pH 7.0. The exchangeable sodium percentage (ESP) was calculated using this data.

The consistency limits experiments (Liquid Limit LL and Plastic Limit PL) were conducted using the method described in Australian Standard (AS 1289.3.1.1-1995).

#### 4. Results and Discussion

At the initiation of the experiments, amperages of approximately 200 mA and 270mA were recorded for soil S1 and soil S2 respectively. With time, the flow of current through the soil started to decrease and dropped significantly to a level of less than 10 mA, in about 10 to 14 days (Figure 1). This indicated that the electrokinetic processes become quite inactive after about 14 days. Therefore, the results reported in this paper are for an electrokinetic treatment period of 14 days.

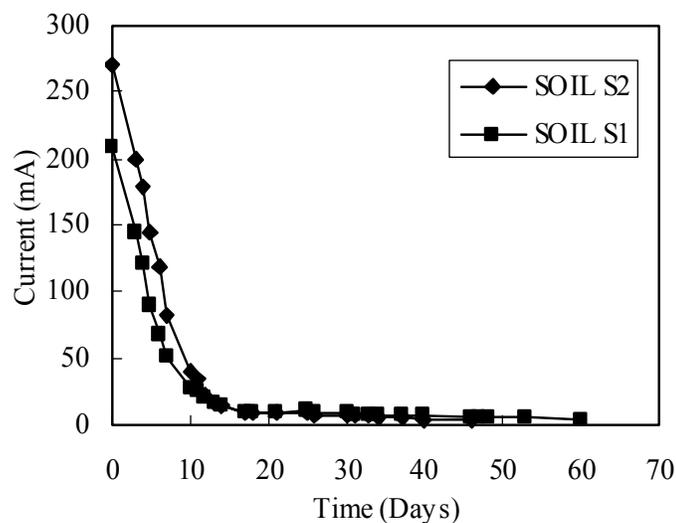
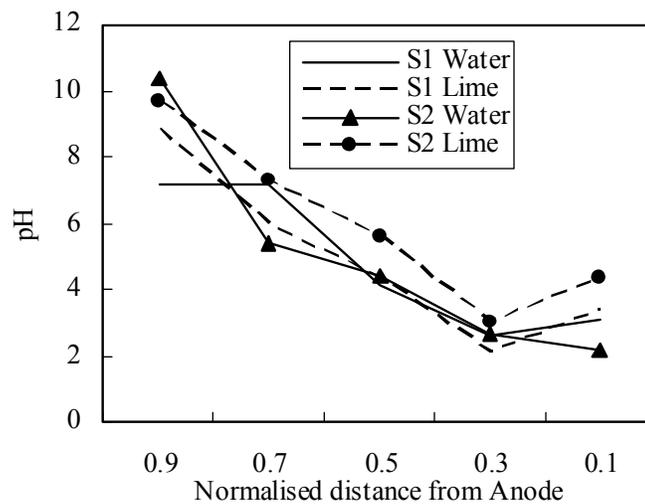


Figure 2. Variation of current flow across the tank with time

#### 4.1 VARIATION OF SYSTEM CHEMISTRY AND THE EFFECTS ON pH AND EC

There are several different chemical, electrical and electrochemical processes that become active within the soil-liquid medium, when a soil is subjected to electrochemical processing. These processes change the system chemistry and collectively affect the soil micro-structure and consequently modify many soil properties.

The results of pH variation across the tank with distilled water and lime enhancement are presented in Figure 3. It is observed that a clear pH gradient is developed across the tank creating an acid front at the anode and a base front at the cathode. With the lime introduction, there is a decrease in the acidity at the anode. This is due to the inverse effects of highly alkaline lime has on the development of acid front.



*Figure 3.* Variation of pH across the tank with lime and distilled water enhancement

The corresponding variation of electrical conductivity ( $EC_{1.5}$ ), across the tank is presented in Figure 4. It is observed that the electrical conductivity of soil is fairly high closer to anode (normalised distance 0.3 from anode) and the middle of the tank (normalised distance 0.5 from anode). In general, across the tank, the EC values are gradually reducing from anode towards

cathode. The lowest electrically conductive zone occurred closer to the cathode with a normalised distance of 0.7 from anode.

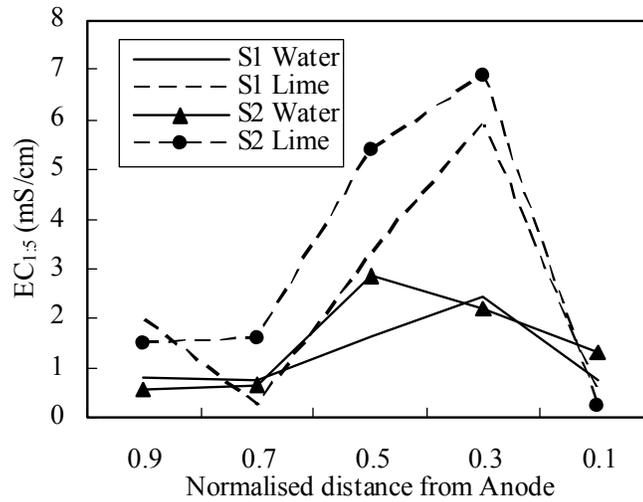


Figure 4. Variation of EC1:5 across the tank with lime and distilled water enhancement

The high EC values observed towards the anode are due to the generation of  $H^+$  ions that are conductive (mobile) in solution and the gradual migration of these  $H^+$  ions from anode towards cathode. The high EC valued in the middle of the tank indicates the electromigration of both the hydrogen ions and calcium ions produced at the anode. The somewhat lower electrical conductivity value observed at the cathode are due to the neutralisation of alkali front, which is associated with the calcium hydroxide ( $Ca(OH)_2$ ) precipitation under the alkaline conditions at the cathode.

At the anode, the mild steel electrodes oxidise and produce  $Fe^{3+}$ . These ions are also susceptible to migrate from anode towards cathode and interact with clay minerals. Hence, these ions could also contribute to the electrical conductivity of the soil at different regions. However it was not attempted to quantify these parameters in this series of experiments.

The electrical conductivity of the soil at any given location along the soil cross section depends on the amount of ions present. However, since  $H^+$  ions are more mobile in solution compared to

other ions, the concentration of  $H^+$  ions contributes greatly to the electrical conductivity of the soil. Thus, when soils are subjected to electrochemical processing, the electrical conductivity alone is not a good measure to access the degree of soil salinity since EC is greatly influenced by the presence of  $OH^-$  and  $H^+$  ions in the pore solution.

#### 4.2 VARIATION OF DISPERSION CHARACTERISTICS

The ESP and SAR were used to assess the dispersion characteristics and the sodicity of the test soils. As can be seen from Figure 5 and Figure 6, there are remarkable decreases in ESP and SAR for both soils up to about a normalized distance of 0.7 from anode. ESP for both soils is generally less than 6 with a few exceptions (original ESP 34 for Soil S1 and 31 for Soil S2) while SAR is lower than 3 (original SAR 8 for soil S1 and 9 for soil S2). According to classifications proposed to assess the degree of sodicity using ESP and SAR, the soil in these areas can now be classified as having a very low to negligible sodicity. In other words, soils in these regions are significantly less dispersive than the original untreated soil.

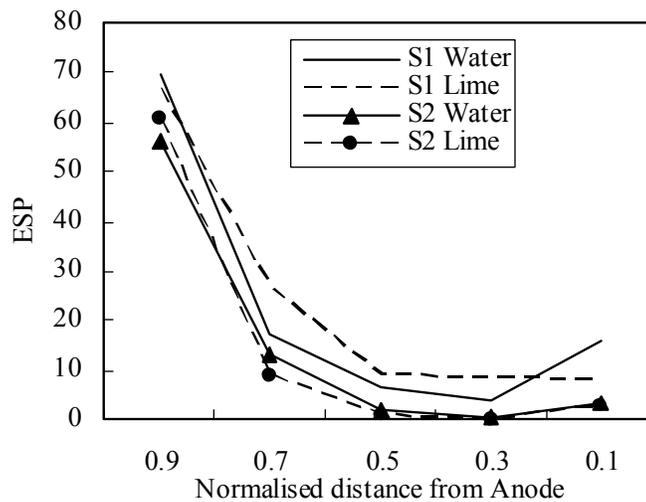


Figure 5. Variation of ESP across the tank with lime and distilled water enhancement

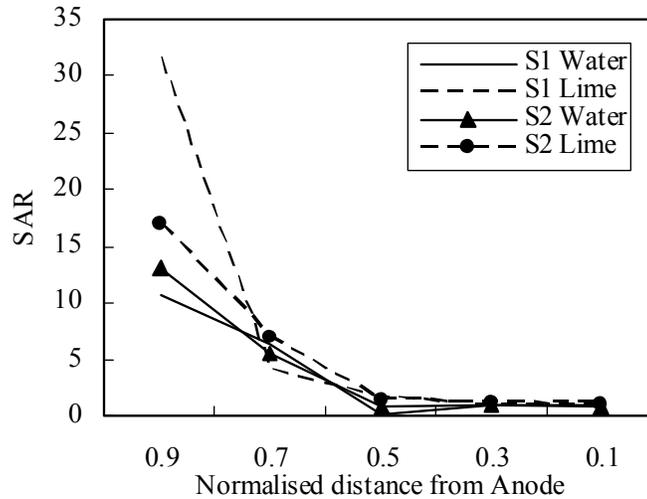


Figure 6. Variation of SAR across the tank with lime and distilled water enhancement

#### 4.3 VARIATION OF COMPRESSIVE STRENGTH CHARACTERISTICS

As can be seen from Figure 7, there are significant variations in the compressive strengths of soils S1 and S2 after 14 days of electrochemical processing. The following major electro-chemical processes have contributed to the modification of soil strength.

- (i) Electroosmosis, which is the migration of water through the capillary network of soil particles under the influence of an electric field. With the electroosmotic flow, the moisture condition across the soil changes. As differential in soil zeta potential develops (associated with the changes in soil pH and also the changes in the chemical concentrations in the pore solution) a change in the electroosmotic potential occurs across the tank. With time, certain areas in the tank start to dry out relative to other areas. The location of wet and dry regions depends on the soil mineralogical properties such as permeability characteristics, clay type and content, DDL characteristics etc. This phenomena is discussed in some detail by (Jayasekera et al. 2004; Ugaz et al. 1994). For the test soil S1, the driest area occurs at a normalised distance 0.7 from anode while for soil S2, the driest area is at a normalised distance 0.3 from anode. As can be seen from

Figure 7, there is a significant increase in the UC strength corresponding to the driest region across the soil.

- (ii) Electromigration, which is the transport of charged chemical species under an electrical gradient). The transport of  $\text{Ca}^{2+}$ ,  $\text{Na}^+$  and other charged ions and their interaction with clay minerals can also affect the soil strength due to the variations in the DDL ionic concentration and subsequent modifications in the soil structure. In response to the decrease in soil dispersion due to the  $\text{Ca}^{2+}$  introduction with lime enhancement, an increase in the soil compressive strength is evident for both soils S1 and S2, between the normalised distances of 0.2 to 0.8 from anode.
- (iii) With the introduction of lime, several short-term and long term chemical reactions take place that alter the soils physico-chemical properties (Sherwood 1993). The exothermic formation of  $\text{CaOH}_2$  results in significant improvements in soil workability purely due to dewatering. The release of Ca and OH ions into the pore solution and subsequent cation exchange (substitution of calcium ions for the existing cations at negative sites on the clay surface) and agglomeration-flocculation reactions suppress the thickness of the diffused double layer and reduce the soil dispersion and soil sodicity. With time, the pozzolanic reactions take place and form cementing bonds and cementing compounds within the pore space and soil particles. These consequences modify many engineering characteristics such as dispersion, strength, plasticity, volume change potential, permeability and compressibility (Kennedy et al. 1987; Rogers et al. 2003).

These reactions have contributed towards the soil strength as evident from the recorded significant increases in the strength for both soils S1 and S2 with lime enhancement. With distilled water enhancement, the increase in the compressive strength is in excess of 100% while with lime enhancement the strength increased by almost 200%. This was the most noticeable effect of lime introduction with electrokinetic treatments.

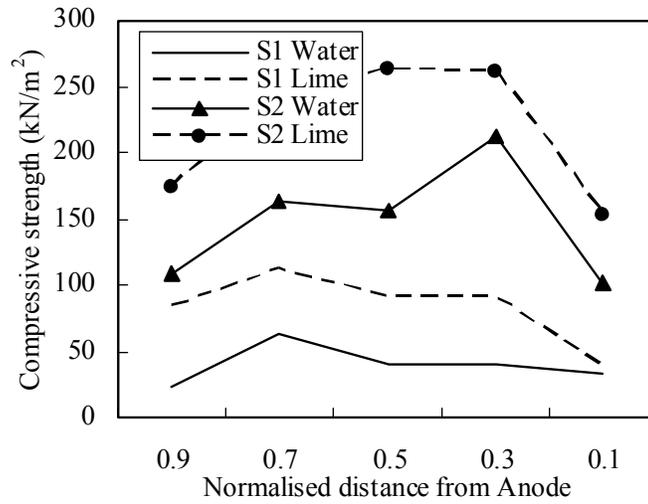


Figure 7. Variation of compressive strength with lime and distilled water enhancement

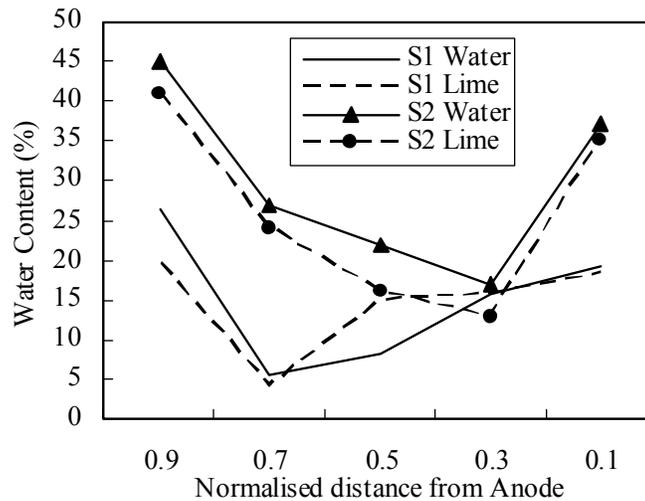


Figure 8. Variation of water contents of soil S1 and S2 with lime and distilled water enhancement

#### 4.4 VARIATION OF PLASTICITY CHARACTERISTICS

The effects of electrokinetic processing on plasticity characteristics were evaluated using consistency limits. The plasticity properties of a soil depend on the soil water content and also on the variations in the chemistry of the pore solution.

**Table 2.** Consistency properties of soil with lime and distilled water enhancement

Soil Type	Status	Anode enhancement liquid	Normalised distance from Anode	Atterberg Limits		
				LL	PL	PI
S1	(unprocessed)			30	23	7
	Electrochemically processed for 14 days	Distilled water	0.3	29	21	8
			0.7	33	26	7
		Lime Solution	0.3	31	25	6
			0.7	33	27	6
	(unprocessed)			72	34	38
S2	Electrochemically processed for 14 days	Distilled water	0.3	69	30	39
			0.7	75	34	41
		Lime Solution	0.3	76	40	36
			0.7	73	38	35

It is observed that there are noticeable increases in the LL and PL in the cathode end. In this area, due to ionic redistributions, the soil has a higher pH indicating more surface negativity. As such there is a corresponding increase in the LL and PL. The majority of sodium ions that have travelled towards the cathode end region can also affect this increase in the LL and PL. Towards the anode end, the pH is lesser with distilled water enhancement than with lime enhancement. Therefore, a reduction in the LL and PL is observed in the anode end region for distilled water enhanced soils whilst with lime enhancement, an increase in LL and PL is noted. This is due to the inverse effects of lime has on the pH and subsequent effects on clay surface negativity.

With lime enhancement, there is a decline in the PI due to the increase in both LL and PL. This variation is more prominent for soil S2 which contained a higher clay fraction whilst soil S1 also shows the same trend although the variations are marginal. These observations are generally in conformity with the observations made by (Rogers et al. 2003) and (Sadrekarimi and Sadrekarimi 2003), in electrokinetic stabilisation of clay soils using lime. In general, a decrease in PI value indicates the effects of agglomeration-flocculation reactions and the subsequent pozzolanic reactions that lead to decrease in soil plasticity, a major benefit in lime stabilisation.

From the laboratory experiments conducted it is evident that electrokinetic treatments techniques can be used to modify many physico-chemical properties of saline-sodic soil. This technique would be especially viable when there is an immediate need for treatment and enhancement of physical properties of soil in a locality, within a short time frame, in the maintenance and protection of infrastructure from adverse salinity effects. Similarly, there is possibility of using this technique to remediate and clean up already salinised land to prepare for new infrastructure development and reduce the significant costs that could otherwise be associated with higher construction costs, higher grade material costs and increased maintenance costs. Electrokinetic techniques would also be an attractive alternative to introduce lime and or other desirable chemical compounds to the soil especially when conventional mixing is not possible for reasons of time constraints, access and depths.

## **5. Conclusions**

This paper presents laboratory experimental results of a study undertaken to investigate the effects of electrochemical treatments on the properties of a saline-sodic soil. From the results presented, the following conclusion can be made.

- (i) With electrokinetic treatments, the ESP and SAR decreased significantly across the soil indicating that the treated soil is almost 90% less dispersive. The sodicity decreased to a level where the degree of effects of soil sodicity would be negligible. For this series of experiments, the lime introduction did not influence the variation in the ESP and SAR to a noticeable extent.
- (ii) The increase in the compressive strength was in excess of 100% with electrokinetic treatment alone while the lime introduced electrochemical processing lead to almost 200% strength increase. The soil type, clay content and various complex electro-chemical processes initiated within the medium influences the variation in the compressive strength.
- (iii) The consistency limits change with the electrochemical treatments. With electrokinetic processing alone, the LL and PL increased in the cathode end and reduced in the anode

end. With available results, no definitive conclusion could be drawn as to the overall effect on PI. However, with lime enhancement, there is a noticeable decline in the PI due to the increase in both LL and PL

## **6. Acknowledgements**

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