Electrokinetic treatment on a tropical residual soil

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The results of shear box and consolidation tests on electrokinetically-treated tropical residual soil are presented. Injections of selected chemicals (calcium chloride, aluminium chloride and phosphoric acid) into the soil samples at the anodes or cathodes were carried out in cylindrical electrokinetic cells via applications of 30 V DC electrical potential for 168 h. Four different open-anode and open-cathode electrokinetic systems utilising different anolytes and catholytes were employed to treat the soil samples. The shear resistances of the treated soil utilising distilled water as the anolyte and 1.0 mol/l phosphoric acid as the catholyte was enhanced, whereas the treated soil near the cathode showed significant reduction in compressibility. Soil treated utilising the other chemicals showed no significant changes.

Notation

C_c	compression index
C_s	swelling index
c_v	coefficients of consolidation
e/e_0	normalised void ratio
k	hydraulic conductivity
m_v	average volume compressibility
w_{opt}	optimum moisture content
σ_y	yield stresses
σ_c	pre-consolidation pressures
ρ_{dmax}	dry density

1. Introduction

Several methods have been employed worldwide to improve the engineering characteristics of soils so as to increase shear strength and to reduce compressibility. Such methods can be categorised into different classes of stabilisation, namely mechanical, chemical, thermal and electrical. With regard to tropical residual soils, the shear strength decreases and the compressibility increases when the soils are saturated. Reductions of up to 50% in cohesion intercept and about 30% in internal shear resistance as a result of saturation of lateritic soils were reported by Sridharan (1988).

In relation to electrochemical treatment to stabilise soils, chemicals are introduced at the anode or/and cathode, either in solution or by decomposition of the electrodes. As a result, the treated soil

is strengthened due to the formation of cementing compounds that are highly resistant to shear and deformation. In the present state, most electrokinetic (EK) processing is performed on soils of temperate zones, particularly kaolinite. Therefore, a laboratory study was initiated to investigate the effects of types of anolyte and catholyte on the shear resistance and compressibility of an electrokinetically-treated Malaysian granite residual soil. Enhancement of the engineering properties was anticipated by precipitation of the introduced ions.

2. Electrokinetics

Electrokinetic phenomena in a porous medium are basically based on the relative motion between a charged surface and the bulk solution at its interface. The formation of an electric double layer at the charged surface of clay particles is responsible for EK phenomena of interest, namely electrophoresis, electromigration and electroosmosis (Mitchell, 1993).

In electroosmosis, electrolysis of water at the anode and the cathode produces oxygen and hydrogen, respectively, which can be represented by the following equations:

Based on Equations 1 and 2, it is noteworthy that both H^+ and OH^- migrate across the soil sample towards the cathode and the anode, respectively during the course of EK processing. In addition, many complicated electrochemical phenomena that are dynamic, reversible and interdependent can change the EK properties of soil particles and the chemistry of pore fluid simultaneously (Yeung and Hsu, 2005).

Low permeability soils which cannot be successfully drained by methods such as sheeting and open pumping can be drained with the help of electrical flow (Chappell and Burton, 1975). Several researchers (Esrig, 1968; Johnston and Butterfield, 1977; Othman and Shafii, 1990) had conducted bench-scale experiments to investigate the effects of electroosmosis on engineering properties of soils, while field tests performed by other researchers (Chappell and Burton, 1975; Fetzer, 1967; Lo and Ho, 1991) justified the applicability of the process.

Electrokinetic processing has also been employed with the combination of chemical solutions to increase strength of low hydraulic conductivity cohesive soils. These chemical solutions can be fed at the anode or the cathode depending upon the ions to be transferred into the soil. The chemical substances utilised include among others calcium chloride (Barker *et al.*, 2004; Harton *et al.*, 1967), aluminium chloride (Gray, 1970), sodium silicate (Barker *et al.*, 2004) and aluminium sulfate and phosphoric acid (Ozkan *et al.*, 1999).

3. Soil properties

The particle size distribution of the soil used in this study as obtained based on sieve analysis and hydrometer test is illustrated

Figure 1. Particle size distribution of soil

in Figure 1 and the basic engineering and chemical properties are tabulated in Table 1. This soil was classified as silt of very high plasticity with gravel (MVG) based on BS 1377: Part 2 (BSI, 1990a). The ratio of silicon dioxide (SiO_2) to aluminium oxide (Al_2O_3) yielded a value of 1.01 indicating that the soil used in this study is a laterite (Mitchell, 1993).

X-ray diffraction (XRD) analysis was performed in which a powder-like ground soil sample was analysed for its compounds using a diffractometer. The diffractogram was redrawn as shown in Figure 2 and was referred to the Joint Committee on Powder Diffraction Standards (Berry, 1974) for mineral identification. The result showed that the predominant minerals present were kaolinite, quartz, gibbsite and goethite.

Properties	Values	References/methods
Specific gravity	2.71	BS 1377: Part 2:1990 (BSI, 1990a)
Natural moisture content: %	3.65	BS 1377: Part 2:1990
Liquid limit: %	74.50	BS 1377: Part 2:1990
Plastic limit: %	49.00	BS 1377: Part 2:1990
Plasticity index: %	25.50	BS 1377: Part 2:1990
Shrinkage limit: %	18.31	BS 1377: Part 2:1990 (volumetric)
pH	5.30	BS 1377: Part 3:1990 (BSI, 1990b)
Organic: %	2.00	BS 1377: Part 3:1990 (peroxide)
Chloride: % (water soluble)	0.012	BS 1377: Part 3:1990 (UV visible)
Sulfate: % (water extract)	5.85	BS 1377: Part 3:1990 (UV visible)
Carbonate: %	0.20	BS 1377: Part 3:1990 (UV visible)
Maximum dry density: kg/m^3	1415.00	BS 1377: Part 4:1990 (BSI, 1990c)
Optimum moisture content: %	33.00	BS 1377: Part 4:1990
Hydraulic conductivity: m/s	3.60×10^{-8}	Head (1982)
CEC: meq/100 g soil	1.00	Moris and Singh (1980)
AEC: meq/100 g soil	1.30	Hesse (1972)

CEC, cation exchange capacity; AEC, anion exchange capacity

Table 1. Engineering and chemical properties of the soil

Figure 2. Redrawn diffractogram of residual soil used in this study

From measurements made based on BS 1377: Part 3 (BSI, 1990b) with slight modification to suit the EK cell, it was learnt that the average resistivity of the compacted and saturated samples (C&S) was approximately $1 \times 10^5 \Omega \text{ cm}$, higher than the range of values from 5×10^2 to $5 \times 10^4 \Omega \text{ cm}$ as reported by geophysicists (Hausmann, 1990). The high resistivity, low cation exchange capacity (CEC) and anion exchange capacity (AEC) of the soil might be associated with the intensive weathering and the high annual rainfall (between 1700 and 3500 mm) that leached away the dissolved constituents from the soil (Gidigas, 1976). Nonetheless, the low value of the CEC obtained in this study was in general agreement with soils containing high iron and aluminium oxides (Brady and Weil, 1996).

The procedures to determine the CEC are described by Moris and Singh (1980). In this regard, a soil sample was left inundated overnight in 1.0 mol/l ammonium acetate in a flask after which the valve of the flask was opened slightly so that the liquid dripped slowly. The liquid collected was analysed for calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+) and potassium (K^+) using an atomic adsorption spectrophotometer (AAS).

The AEC was determined based on the quantity of extractable and adsorbed phosphorus as described by Hesse (1972). In summary, the dry soil sample was leached with triethanolamine solution and washed using ethanol. The sample was dried after leaching with calcium chloride and was agitated after adding 0.01 mol/l of phosphoric acid. Then the liquid was analysed using AAS to determine the adsorbed phosphorus.

In a separate sample, the phosphorus was extracted using 0.03 mol/l ammonium fluoride in 0.1 mol/l hydrochloric acid. A soil/solution ratio of 1:20 was applied in the extraction process. The mixture was shaken and filtered, after which the content of phosphorus in the filtrate was determined using AAS.

4. Experimental procedures

4.1 Sample preparation

A residual soil was obtained from a depth of 2 to 3 m below the ground surface. The soil was air-dried under laboratory conditions, after which pebbles and plant roots were removed. Only soil passing a 2.00 mm sieve was used in the EK experiments and other related tests. Then the sieved soil was mixed thoroughly in order to ensure homogeneity of the sample and kept in a securely tied large plastic bag to prevent or minimise the effects from the surrounding environment.

Soil samples with a dry density approximately 90% ρ_{dmax} at its corresponding w_{opt} were chosen as the basis of sample preparation for EK treatment. The ρ_{dmax} and w_{opt} were determined based on the standard Proctor compaction tests (BSI, 1990c). The diameter and length of each soil compartment of the EK cell utilised in this study were 100 and 50 mm, respectively. Non-conductive silicon grease was thinly applied onto the inner surface of the soil compartment to avoid the formation of water film between the soil and the inner wall of the cylinder. This precaution was to ensure that water would only flow through the soil, not through channels between the soil and the wall of the cylinder during EK processing.

Every sample of soil and distilled water weighing about 666 g prepared for EK treatment was then poured into the soil compartment. A triaxial test frame was utilised to press the sample until a predetermined thickness of about 5.0 cm was achieved to obtain the required bulk density of 1695 kg/m^3 . Then each sample was subjected to saturation.

4.2 Electrokinetic experiments

The EK experimental set-up is shown in Figure 3. Titanium meshes were utilised as the electrodes due to its high resistivity to corrosion (Berkeley and Pathmanaban, 1990). Flexible rubber tubes with an inner diameter of about 6 mm were utilised as inflow and outflow tubes. Glass tubes acting as gas vents were attached to the top of the electrolyte compartments to facilitate liberating gas from the system.

The only electrical parameter held constant in these EK experiments was the applied voltage, namely 30 V. This value was chosen because attempts to apply lower voltages failed to produce flow after 2 days of EK treatment using distilled water as both the anolyte and catholyte. Four different open-anode and open-cathode EK systems were employed, which consisted of

- distilled water as both the anolyte and catholyte (DW–DW)
- 1.0 mol/l aluminium chloride as the anolyte and distilled water as the catholyte (Al–DW)
- 1.0 mol/l calcium chloride solution as the anolyte and distilled water as the catholyte (Ca–DW).

Figure 3. Schematic diagram of the EK experimental set-up

(d) distilled water as the anolyte and 1.0 mol/l phosphoric acid as the catholyte (DW–PA).

Note that the left and right terms in each parenthesis represent the anolyte and catholyte, respectively. The selection of the chemical substances was based upon the types that have been utilised successfully on temperate soils, particularly kaolinite by previously mentioned researchers such as Gray (1970) and Ozkan *et al.* (1999). The duration of each EK treatment was 168 h (7 days) based on studies on electroremediation by Thevanayagam and Wang (1994), Taha (1996) and Park *et al.* (2005). Principally two samples were treated electrokinetically for each anolyte–catholyte system, one for strength test and the other for consolidation test.

4.3 Shear box tests

After termination of EK processing, each treated sample was extruded and divided into two parts, namely the cathode side and the anode side. Then each part of the treated sample was subjected to strength test using a standard 60 mm × 60 mm × 20 mm shear box. A normal stress of 40 kPa representing the in situ overburden stress from which the soil sample was obtained was applied to each specimen during shear. Note that the typical unit weight of soil in this region is within a range between 17 and 20 kN/m³. Each sample was subjected to quick

test with the anticipation that failure would be reached within 5 to 10 min (BSI, 1990d). Thus, a shearing rate of 0.60 mm/min was selected taking into account the shear box travelled into its full length. No attempts were made to cure the treated samples with the expectation that the treated samples should gain strength during or immediately after treatment.

4.4 Compressibility tests

After termination of EK processing, each treated sample was extruded and divided into two parts, namely the cathode side and the anode side. Then each part of the treated sample was subjected to a one-dimensional consolidation test in accordance with BS 1377: Part 5 (BSI, 1990e) using a 50 mm diameter and 20 mm high consolidation ring. As in the case of strength tests, no attempts were made to cure the treated samples.

5. Results and discussion

5.1 Shear resistance

Figures 4 and 5 show the plots of shear stresses against axial strains obtained from the direct shear tests on the samples within the vicinity of the anodes and cathodes, respectively. The ultimate shear stress values deduced from these figures are tabulated in Table 2.

Figure 4. Shear resistances of samples after EK treatments near anodes. Note: terms on the left and right of hyphens indicate anolyte and catholyte, respectively: Al, aluminium chloride; C&S, compacted and saturated (no EK treatment); DW, distilled water; Ca, calcium chloride; PA, phosphoric acid

Figure 5. Shear resistances of samples after EK treatments near cathodes. Note: terms on the left and right of hyphens indicate anolyte and catholyte, respectively: Al, aluminium chloride; C&S, compacted and saturated (no EK treatment); DW, distilled water; Ca, calcium chloride; PA, phosphoric acid

To examine the effect of EK treatments, the shear resistance of the compacted and saturated sample (C&S) that was not treated electrokinetically was utilised as a reference. For samples that did not exhibit any peak values of shear resistance under different strains, the ultimate shear stress was defined at the point where the slope of the shear stress–strain curve first reached a steady minimum value (Hanna and Abd El-Rahman, 1990).

5.1.1 Compacted and saturated sample without EK treatment (C&S)

It was found that the average maximum shear stress of the C&S samples was about 31 kPa as shown in Figures 4 and 5. The shear resistance achieved was possibly due to cohesion, surface friction as well as the packing and orientation of the soil particles. The cohesion contributing to the shear resistance was the result of factors such as cementation and might be oxides of iron or aluminium (Blight, 1997; Fookes, 1997).

5.1.2 DW–DW system

Strength reduction was observed as certain compounds contributing to the strength of the soil would be ionised by the migration of H^+ across the soil samples (Ozkan *et al.*, 1999) which led to an acidic environment due to the prolonged EK process. An acidic environment was also observed by Yeung and Hsu (2005) in a study on EK remediation. In addition, no cementation was anticipated to take place during the course of the experiment as cementation would only take place if suitable ions such as iron (Bell, 1975), calcium (Esrig and Gemeinhardt, 1967; Harton *et al.*, 1967), or aluminium (Gray, 1970; Murayama and Mise, 1953) were present in the system.

5.1.3 Ca–DW system

Calcium ions will only react with clay minerals to form cementitious materials under a highly alkaline environment,

EK system	Shear stress: kPa (anode)	% increase (anode)	Shear stress, kPa (cathode)	% increase (cathode)
C&S (No EK)	31	0	31	0
DW–DW	21	–32	21	–32
Al–DW	12	–61	12	–61
Ca–DW	15	–52	31	0
DW–PA	35	13	83	168

Table 2. Ultimate values of shear resistance after EK processing

namely a pH of 12.4 (Glendinning and Rogers, 1996). An environment with lower pH than 12.4 might cause calcium to remain ionic. As a result of the acidic environment within the vicinity of the anode area (pH = 5.3) and slightly alkaline near the cathode area (pH = 7.53) due to the EK processing, no cementitious materials contributing to the strength increase were formed. Thus, the treated samples showed no improvement in shear resistance.

The results obtained in this study however contradicted those obtained by Harton *et al.* (1967) who employed EK to treat clay soil combined with the injection of calcium chloride and followed by the injection of aluminium sulfate. It can be deduced from their results that the electrokinetically injected calcium ions required secondary chemical injection to increase the strength of the treated soil.

Figures 6 and 7 show the images of the soil fabrics near the anode and cathode after Ca–DW treatment, respectively. An electron microscope was employed to obtain images of the microstructures of the untreated and the EK-treated soils. Briefly, dried samples were coated with thin gold film using a sputter coater after which the gold-coated samples were placed in the vacuum compartment of the electron microscope to obtain their images at selected magnifications.

From Figure 6, it is believed that the coating materials (oxides of iron or aluminium) were dissolved due to the acidic environment or other chemical reactions that took place near the anode thus exposing the platy-shaped particles. On the other hand, Figure 7 shows large interconnected soil particles in the background besides randomly arranged small nodules in the foreground of the sample near the cathode. Ion exchanges that altered the property of the material as found by Esrig and Gemeinhardt (1967) might have led to such fabric or particle arrangements.

Figure 6. Image of soil fabric treated using Ca–DW system near anode

Figure 7. Image of soil fabric treated using Ca–DW system near cathode

5.1.4 Al–DW system

The strengths of the samples treated using this system were reduced both near the anode and the cathode. These observations contradicted the results obtained by Murayama and Mise (1953), Harton *et al.* (1967) and Gray (1970). Testing after the EK processing showed that the pH of the soil near the anode decreased from 5.30 to 3.29, whereas near the cathode the soil pH decreased to 3.55. Thus, the reduction of shear resistance of the treated soil was associated with the acidic environment in the soil. A previous study by Yamaguchi and Matsuda (1975) showed that neutral pH was necessary for full precipitation of aluminium hydroxide ($\text{Al}(\text{OH})_3$) to take place.

The reduction in the soil pH at the cathode after treatment indicated that the amount of H^+ that migrated across the soil exceeded the quantity of the OH^- that migrated towards the anode due to the prolonged EK treatment. Such phenomena took place since twice as much H^+ would be generated by the electrolysis of water at the anode in comparison with the generation of OH^- at the cathode, and Acar *et al.* (1990) found that the acid front moved over a much greater distance than the base front. The acidic environment due to the migrated H^+ into the soil might have altered the chemistry of the pore fluid (Ozkan *et al.*, 1999), which led to ionisation of certain minerals.

An earlier study by Gray (1970) showed that the utilisation of a 1% solution of AlCl_3 as the anolyte and a 0.5% solution of NaCl as the catholyte to treat bentonitic and illitic soils were able to increase the strength of the treated soils. The strength increase was enhanced after the treated soils were cured for a month. In comparison with the previous work by Gray (1970), note that the residual soil samples were not cured after EK treatment in which 1.0 mol/l AlCl_3 and distilled water were used as the anolyte and catholyte, respectively. Thus, a curing period might be required so that hydroxides of aluminium compounds would harden and increase the strength of the treated soils in addition to introducing secondary chemical during the EK processing.

On the other hand, Murayama and Mise (1953) showed that the strengthening of clay soils treated electrokinetically by the injection of Al^{3+} would only take place once the precipitated $\text{Al}(\text{OH})_3$ was dehydrated to become bauxite ($\text{AlO}(\text{OH})$) and alumina (Al_2O_3) as described by the following equation

It was suspected that the $\text{Al}(\text{OH})_3$ within the treated residual soil near the cathode in this study remained as gel as no dehydration process took place after the completion of EK treatment. Such compound could cause lubrication between the soil particles during shear, resulting in the strength reductions.

Figures 8 and 9 illustrate the images of the soil fabrics of the treated sample near the anode and cathode, respectively. Near the anode, stacks of flaky particles and small nodules are visible

Figure 8. Image of fabric after Al–DW treatment near the anode

Figure 9. Image of fabric after Al–DW treatment near the cathode

within the treated soil matrix. Dissolution or ionisation of the coating materials and other compounds or precipitates due to the acidic environment as stated previously might be the reason for the exposed flaky particles.

Near the cathode on the other hand, some cemented soil particles can be observed in the background of the image with randomly arranged and irregularly shaped nodules as well as flaky-shaped particles in the foreground. Such coating materials might be compounds containing Al^{3+} . Note that such compounds did not contribute to strength increase as those compounds were in hydrated forms.

5.1.5 DW–PA system

The shear resistances of the soil after EK treatment increased to 35 and 83 kPa near the anode and cathode, respectively. These values represent strength increases of 13% near the anode and 168% near the cathode. The formation of phosphate compounds as coating and cementing agents might be the most probable reason for the high value of shear resistance achieved by the treated soil. It was suspected that the low amount of phosphate within the vicinity of the anode resulted only in a slight increase in shear resistance in comparison with the significant increase near the cathode.

As the soil used in this study contained aluminium and iron in addition to the acidic condition of the soil before and after EK treatment, it was suspected that aluminium or iron phosphates were formed contributing to the increase in shear resistance after the DW–PA treatment. It was anticipated that Al^{3+} was released due to the acidification of residual soil (Gidigas, 1976). Hence, the most probable compound formed as a result of the injection of phosphate ions was that of hydrated aluminium phosphate. Attempts made on the basis of an XRD study to identify the formation of new minerals or compounds on the DW–PA treated samples immediately after completion of the processing were unsuccessful. It was hypothesised that the new and fresh cementing compounds were in a non-crystalline or an amorphous form.

Figures 10 and 11 illustrate the images of the samples near the anode and cathode, respectively. Near the anode, it can be seen that the soil in the background was tightly packed with some voids as shown by the dark spots, whereas various sizes of nodules with irregular shapes are visible in the foreground. Near the cathode, the soil particles were interconnected and coated by phosphate compounds to form large particles with some large voids and nodules of various sizes. Ion exchange, acidification, formation of phosphate compounds or other chemical reactions resulting from the EK treatment might be the possible reasons for such soil fabrics.

5.2 Compressibility

As the initial void ratios of the treated samples were slightly different from each other due to sampling procedures, normalised void ratios were utilised in the construction of the compression

Figure 10. Image of fabric of DW-PA treated sample near anode

Figure 11. Image of fabric of DW-PA treated sample near cathode

curves. The normalised values were obtained by dividing the void ratios at different stresses by the initial void ratio of the respective samples. Consequently, all compression curves had the initial normalised void ratio of unity. The discussion hereafter will be based on the results from consolidation tests as shown in Figures 12 and 13.

As disturbed samples were utilised for the consolidation tests, yield stresses (σ_y) will be referred to in the discussion instead of pre-consolidation pressures (σ_c). The selection of the yield stress values was based on the definition of maximum curvature (Hanna and Abd El-Rahman, 1990). The compression curve of the compacted and saturated sample (C&S) that was not treated electrokinetically will be utilised as a reference to any changes resulting from the EK treatments. Table 3 summarises the relevant indices and coefficients obtained from the conducted consolidation tests.

Figure 12. Normalised compression curves of electrokinetically treated samples near anodes

Figure 13. Normalised compression curves of electrokinetically treated samples near cathodes.

5.2.1 Compacted and saturated sample without EK treatment (C&S)

It can be seen from those curves that the compression index C_c and swelling index C_s were 0.25 and 0.03, respectively. In an earlier study on a residual laterite soil, Vargas (see Gidigas, 1976) obtained C_c and C_s values of 0.22 and 0.03, respectively. Such C_c values are considered as moderate to intermediate compressibility (Mitchell, 1993).

Figure 12 shows that the σ_y of the soil used in this study was approximately 100 kPa, higher than the maximum overburden pressure of about 60 kPa considering the soil sample was obtained from 2 to 3 m below the ground surface. Hence, the soil

Treatment systems	C&S	DW–DW	Ca–DW	Al–DW	DW–PA
$C_{c(\text{anode})}$	0.25	0.24	0.23	0.25	0.24
$C_{c(\text{cath})}$	0.25	0.25	0.24	0.23	0.14
$C_{s(\text{anode})}$	0.03	0.03	0.03	0.04	0.02
$C_{s(\text{cath})}$	0.03	0.03	0.01	0.04	0.01
$c_{v(\text{anode})}$: m ² /year	4.16–7.53	4.41–7.91	1.36–4.33	2.73–5.46	3.48–9.20
$c_{v(\text{cath})}$: m ² /year	4.16–7.53	4.26–7.31	1.13–9.44	9.8–20.3	2.01–7.71
$m_{v(\text{anode})}$ 10 ^{–4} : m ² /kN	1.49	1.4	0.90	1.16	1.23
$m_{v(\text{cath})}$ 10 ^{–4} : m ² /kN	1.49	1.26	1.03	1.12	1.2
$k_{(\text{anode})}$ 10 ^{–10} : m/s	1.93–3.50	1.92–3.44	0.38–1.21	0.98–1.97	1.33–3.52
$k_{(\text{cath})}$ 10 ^{–10} : m/s	1.93–3.50	1.67–2.87	0.36–3.02	3.41–7.07	0.75–2.88
$\sigma_{y(\text{anode})}$: kPa	100	25	200	50	200
$\sigma_{y(\text{cath})}$: kPa	100	100	100	100	400

Note: Determinations of m_v and k were based on 200–800 kPa stress range.

Table 3. Values of indices, coefficients and yield stresses

was apparently ‘overconsolidated’ which could result from several factors such as changes in vertical stress, particle arrangements and porewater pressure during sample preparations, drying to evaporation and natural cementation due to carbonates (Mitchell, 1993).

A wide stress range between 200 and 800 kPa was arbitrarily selected to observe variation in values of coefficients of consolidation (c_v) and hydraulic conductivity (k), if any. The values of c_v varied between 4.16 and 7.53 m²/year and the average volume compressibility (m_v) was 1.49×10^{-4} m²/kN. With the availability of c_v and m_v values, the k values of the untreated soil during consolidation were correlated and determined to fall within a narrow range between 1.93×10^{-10} and 3.50×10^{-10} m/s. These values are two orders of magnitude lower than that obtained directly using variable head permeability tests as shown in Table 1. Changes in particle arrangements and pores sizes, and the bending and crushing of soil particles during the consolidation process were the main reasons for such differences.

5.2.2 EK-treated samples

It can be seen from Table 3 that the C_c of the DW–PA treated sample near the cathode decreased significantly to 0.14 in comparison with that of the C&S sample. The formation of phosphate compounds as coating and cementing agents that were highly resistance to interparticle sliding might be the most probable reason for the reduced value of C_c . The reduction in the C_c also might be associated with the pore water chemistry that depressed the double layer (Mitchell, 1993).

In addition, the σ_y of the DW–PA-treated soil near the anode was increased to 200 kPa, whereas near the cathode it was increased by about 300% to 400 kPa. Such effects might also be caused by the cementation and coating of phosphate compounds on the soil

particles. These compounds encapsulated and linked the soil particles together to form large soil grains and exerted internal effective stress under which the soil was consolidated due to the confinement of the sample in the EK cells. The samples were therefore virtually ‘overconsolidated’ by the EK processing, and this is the reason why the effects of the treatment are permanent (Lo *et al.*, 1991).

The acidic environment generated by the EK process that dissolved certain compounds and increased the lubrication effects between soil particles (Ghazali, 1981) might be the reason for the reductions in σ_y values near the anodes of the DW–DW and Al–DW-treated samples. Swelling of the treated sample near the anode due to direct contact with the anolyte (Taha, 1996) and the released stress during sampling were additional reasons for the reduced σ_y .

No significant changes were observed in other parameters after each EK treatment. For instance, the k values of the EK-treated samples obtained indirectly from consolidation tests were two orders of magnitude lower than that of the EK-treated samples obtained directly based on variable head permeability tests. Overall, the slight changes were mostly associated with the pore water chemistry resulting from complex, dynamic and inter-related chemical processes during EK treatment. Ionisation and desorption of certain ions (Ozkan *et al.*, 1999) also might affect the compressibility and the associated indices and coefficients of the treated soil.

6. Conclusions

Electrokinetic treatments were conducted on a tropical granitic residual soil, after which direct shear and consolidation tests were performed on the treated soil samples. The conclusions that can be drawn from this study are listed here.

- (a) The introduction of phosphate ions significantly increased and decreased the shear resistance and the compression index of the treated soil near the cathode, respectively due to the formation of phosphate compounds.
- (b) The electrokinetically injected calcium and aluminium ions were unable to increase the shear resistance or to reduce the compression indices of the treated soils since the calcium remained ionic whereas the formation of aluminium gel lubricated the soil particles due to the acidic environment.
- (c) The difference in terms of soil parameters and indices near the anode than those near the cathode after each treatment showed the non-homogeneity of chemical precipitation throughout the treated sample.

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