IMPROVEMENT OF EXPANSIVE SOIL BY ELECTRO-KINETIC METHOD

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Abstract

The roadway in Karangjati, Ngawi Regency, East Java, Indonesia, which is underlain by expansive soil, is susceptible to damage due to volume change. This research aims to improve the engineering properties, such as consistency limits, compressibility, and undrained shear strength of the montmorillonite dominated soil in this area using an electrokinetic stabilization method. Four electro-kinetic experiments were conducted using different electrolytes (calcium chloride or pure water) under different conditions (no-flow or flow water). The results show that, pH values of all soil samples decreased at anolyte and increased at catholyte. Atterberg limits of the soil samples were found to increase, where the liquid limit (LL) range of 79.72–86.14%, plastic limit (PL) 25.22–30.80%, and plasticity index (PI) 53.28–60.92, liquidity Index (LI) 0.91–1.08. The compression index C_c was 0.50–0.742. Undrained shear strength of treated soil range of 7–11 kPa. Moreover, strengthening degree of the treated soils achieve 304–556%. The soil improvement was achieved by decreasing the Atterberg limits, and compressibility and increasing the undrained shear strength. Applying calcium chloride and flow water condition were the most effective methods for the soil improvement. The mineralogical compositions of the soil samples did not change after the treatment.

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1 Introduction

In this paper, the application of electro-kinetic method for improvement of the engineering properties of expansive soil sample obtained from Karangjati, Ngawi Regency, East Java, Indonesia is investigated. Most of the roads in Ngawi have been constructed over expansive soil known as very active clayey soils, which swell when wet and shrink when dry (Por, 2012). Thus, the roadway in Karangjati is susceptible to failure due to pavement cracking and deformation. In order to improve the engineering properties of the expansive soil in Karangjati, several electro-kinetic bench scale experiments were conducted.

The electro-kinetic technique is defined as a physical-chemical transport of charge, action of charged particles, and effects of applied electric potentials on formation and fluid transport in porous media (Moayedi *et al.*, 2010). Ionic species in the pore fluid are transported across the soil mass both by electro-migration and by electro-osmotic transport. Electro-kinetic phenomena results from the differential movement of two phases, which are solid and fluid phases, with the interface of an electrical double layer. There are for electro-kinetic phenomena: electro-osmosis, electro-migration, electrophoresis, and streaming potential.
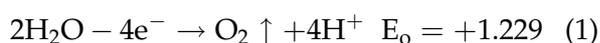
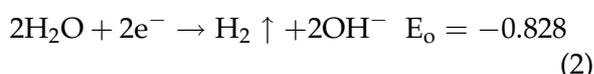Under the influence of an electric field,

cations will move from the anode toward the cathode by both electro-osmosis and electro-migration. On the other hand, electro-migration phenomena cause anions transport in the revese direction of cations transport, i.e., from the cathode to the anode.

With an application of DC current, the oxidation and the reduction will occur in turn at the anode and the cathode (Ahmad et.al. 2006).

Anode:

$$2H_2O - 4e^- \rightarrow O_2 \uparrow + 4H^+ \quad E_o = +1.229 \quad (1)$$

Cathode:

$$2H_2O + 2e^- \rightarrow H_2 \uparrow + 2OH^- \quad E_o = -0.828 \tag{2}$$

where Eo is a standard reduction electrochemical potential. At the anode, the oxidation process generate an acid front, while at the cathode, alkaline will be produced by the reduction process. pH value is different at the electrodes, low pH at the anode, and high pH at the cathode. Therefore, the dissolution of ions will occur near the anode and precipitation occurs near the cathode.

Electro-kinetic treatment induces several changes in the pore fluid chemistry, soil fabric, and hydraulic conductivity. The electro-kinetic process can be enhanced by the use of some non-toxic enhancement solutions (stabilization agents), such as lime or calcium chloride solutions. These chemical solutions can be fed at either anode or cathode depending on the ions to be transferred into the soil. By the addition of an appropriate enhancement agent, some properties of the soil such as texture, plasticity, compressibility and permeability will be altered; therefore they can be very effective in improving soil characteristics by reducing the amount of clay size particles and increasing the shear strength (Nasim, *et al.*, 2012). When cations are used as stabilizing agents, ions migrate into soils through processes of electro-migration and electro-osmosis. These ions improve soil strength by three mechanisms, namely cation exchange, mineralization, and precipitation of species in the pore fluid (Thakur *et al.*, 2011). It

is precipitation or mineralization, that provides the greatest contribution to increase in strength. The reaction usually occurs when pH values of the soil solution are greater than seven. Therefore, the pH values of the soil solution need to be maintained above seven during treatment in order to maximize its efficiency by appropriate injection of chemical ions at both electrodes (Jajudin, 2012).

Monovalent cations, such as sodium and potassium, are commonly found in expansive clay soil and these cations can be exchanged with cations of higher valences, such as calcium. This ion exchange process takes place quite rapidly, often within a few hours. The calcium cations replace the sodium cations around the clay particles, decreasing the size of the bound water layer and enabling the clay particle to flocculate. The flocculation causes a reduction in plasticity, an increase in shear strength of the clay soil, and an improvement in texture from a cohesive material to a more granular, sand-like soil. The change in the structure causes a decrease in the moisture sensitivity and increases the workability and constructability of the soil. The magnitude of soil stabilization is usually measured by the increase in strength as determined from undrained shear strength test (Justin and Robert, 2004).

2 Materials and methods

One natural soil at a site in Karangjati, Ngawi Regency, East Java, Indonesia was taken as soil sample. For electro-kinetic treatment, the samples were prepared near liquid limit condition. The electrolyte solution, which was chosen for treatment, was pure water and calcium chloride with 1 mol/l concentration.

The schematic diagram of test equipment is shown in Figure 1. The soil sample was stored on the central compartment of the container. Anolyte and catholyte were installed on the electrode compartments, which filled with the electrolyte solutions. The compartment A and B were filled with pure water to simulate the ground water in the field. A cotton filter separates the soil sample from four sides of com-

partment to prevent the soil particles to move from one side to the other sides while it allows the movement of water and chemical species. The electrode compartments were filled with (a) pure water and (b) chemical solution that is a 1 mol/l solution of calcium chloride constituted at anolyte and pure water at catholyte. The selection of the chemical substance and its concentration was chosen based upon the types that have been utilized successfully on a research of Ahmad et al. (2011) and Moayedi et al. (2012). The electrolyte solutions need to be observed and maintained (a) no-flow and (b) at flow condition. No-flow condition was created by filling compartment A and B by pure water with 50 mm height. Water was pumped from the compartment A and supply to the compartment B to create the flow condition. The water-level at the compartment A was 50 mm height and the water lever at compartment B was maintained a 3 mm higher than that at the compartment A causing a small flow of water with hydraulic gradient of 0.005.

Two 1 mm-thick of aluminum plates were used as the cathode and the anode. The selection of aluminum electrodes was based on a suggestion of Grey and Schlocker (1969) on their research about electrochemical alteration of clay soils. They noticed two main reasons for choosing Aluminum as electrodes: (1) Aluminum anodes are often used in engineering practice for electro-osmotic dewatering; (2) Aluminum can be combined with hydroxide ions to form various hydroxyls–aluminum compounds in soil. These compounds have interesting properties: they can interlayer with certain clay minerals or precipitate externally in the pore space as amorphous or crystalline hydroxides and thus modify the mineralogy composition, and presumably the physical properties of soil. Szynkarczuk (1994) also mentioned that Aluminum is the preferred material since it does not color the supernatant. Tajudin (2012) confirmed the stabilization effects due to strengthening by electro-kinetic can be enhanced by appropriate choice of the electrode material (aluminum instead of steel) or by the addition of sodium silicate or calcium chloride at the anode

The electrodes were connected to a constant electric current DC power supply with output of 10A at 13V. The weight of aluminum electrodes was measured before and after electrokinetic treatment by an electronic balance to determine the corrosion effect.

Outline of four electro-kinetic experiments conducted in this research is showed on Table 1. For each test, an approximately 2 kg of natural soil was used. The soil specimen was approximately 5 cm thick. In order to achieve near liquid limit condition, the soil specimen was mixed with pure water and covered by a plastic wrap. During the treatment, the pH values of anolye and catholye were measured at the following periods:

- First 12 hours: every 1 hour.
- After 12 hours to 3 days: every 3 hours
- After 3 days: every 6 hours

Each electro-kinetic experiment took approximately 6 days, based on studies conducted by Rustamaji (2007). After the treatment, moisture content test, Atterberg limits test, one dimension consolidation test, un-drained shear strength test, and X-ray diffraction analysis were conducted.

3 Results and discussion

pH value of anolyte and catholyte

Due to electrolysis reactions (i.e., oxidation at the anode and reduction at the cathode), in general, pH value in the anolyte compartment tends to decrease while pH value in the catholyte compartment tends to increase. However, the pH value is also affected by water from two-flanked compartment A and B causing the decrease or increase of pH value in the anolyte and catholye compartment is interrupted.

Figure 2 shows the pH values of anolyte and catholyte of four soil samples after treatment. In general, the disparity of pH value between anolyte and catholyte of Ca-PW-CL and Ca-PW-WF is greater than of PW-PW-CL and PW-PW-WF systems. It confirms that electro-kinetic method is more effectively when using calcium chloride instead of pure water as anolyte. pH
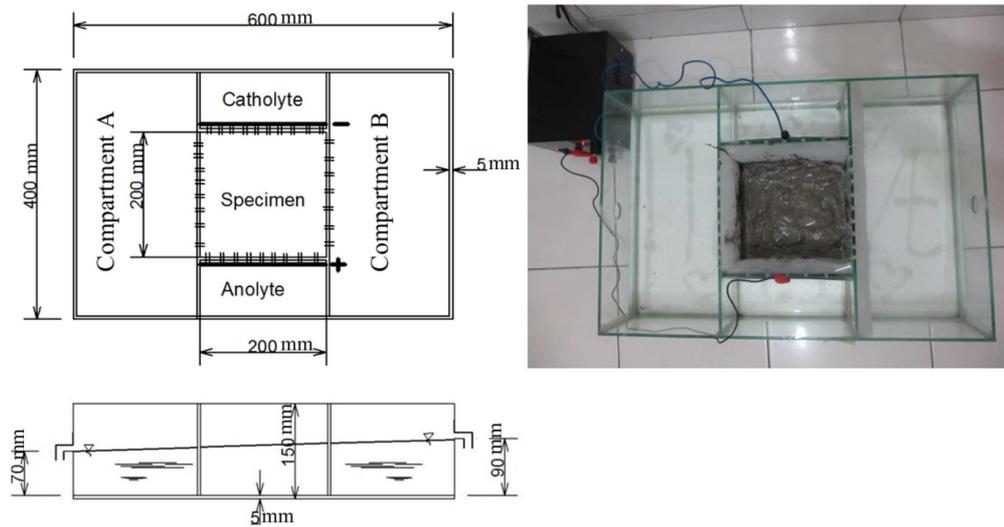
Figure 1: Schematic diagram of the Electro-kinetic bench scale set-up.

Table 1: Electro-kinetic experiments.

Anolyte	Catholyte	Water condition	System
Pure water	Pure water	Constant level	PW-PW-CL
Calcium chloride	Pure water	Constant level	Ca-PW-CL
Pure water	Pure water	Water flow	PW-PW-WF
Calcium chloride	Pure water	Water flow	Ca-PW-WF

value of catholyte PW-PW-CL system is greater than PW-PW-WF system. In addition, pH value of Ca-PW-CL system is greater than Ca-PW-WF system. The results indicate that the anolyte would be less alkaline with water flow condition than with no-flow condition.

Anode corrosion

Aluminum electrodes used in electro-kinetic treatment became a chemically active material. Under apply a DC power, the cation moves to the anode while the anion moves to the cathode. At the anode, the dissolution of aluminum atoms occurs, causing anode to lose its atomic weight. The aluminum ion Al^{3+} moves from the anode torward the cathode, causing the atomic weight of cathode increasing.

The relationship between corrosion at anode and weight increasing at cathode is showed in Figure 3. In all samples, the increase in the weight of the cathode is greater than the lost of weight of the anode (approximately 2 times). This, confirms that the cathode attracts not only the aluminum anions dissolved from the anode but also calcium ions and the anions exist on soil specimen. Degree of anode corrosion of the Ca-PW-CL system and Ca-PW-WF system is higher than the others indicating that anode corrosion by calcium chloride will be higher than by pure water. On the other hand, degree of anode corrosion of Ca-PW-CL system is higher than Ca-PW-WF system and degree of anode corrosion of PW-PW-CL system higher than PW-PW-WF system. This indicates that degree of anode corrosion decreases with flow condition. The high pH value at the catholyte promotes precipitation of calcium and other metals in the cathode. Therefore, the weight of cathode of Ca-PW-CL system increased very high due to its high alkaline environment.

Atterberg limits of treated soil

Table 2 shows the Atterberg limits of the soil before and after electro-kinetic treatments. In general, the liquid limit (wL) and plasticity index (IP) of treated soils became lower than the untreated soil. The decrease in the liquid limit is an indication of the strengthening be-
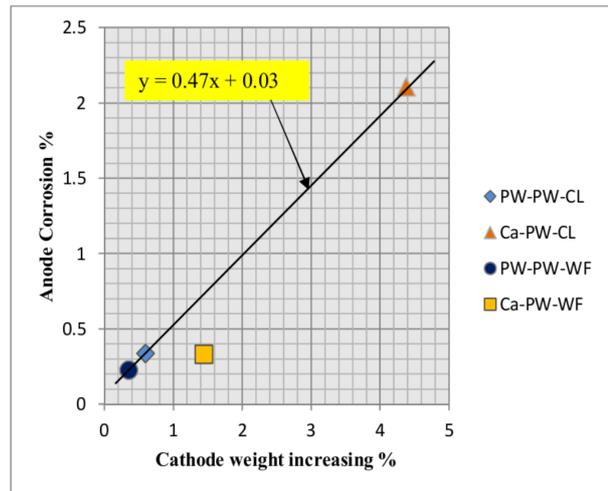

Figure 3: Distribution corrosion effect at the electrodes after electro-kinetic treatment.

havior of soil specimen. The highest liquid limit and plasticity index (i.e., 86.14 and 60.92, respectively), were shown by Ca-PW-CL system, which was treated in no flow condition with calcium chloride at the anolyte. Liquid limit and plasticity index of Ca-PW-WF system. which was treated in flow condition with calcium chloride at the anolyte, were lowest (i.e., 79.2 and 53.28, respectively).

Compressibility of treated soil

Terzhagi and Peck (1967) after Abbasi (2012) established a linear correlation between primary compression index C_c and liquid limit LL for remolded soil follows:

$$C_c = 0.009(LL - 10) \qquad (3)$$

Based on Equation (3), the compression index of untreated soil is estimated to be about 0.753. As the result in Table 4 shows that compression indices, C_c of the treated soils were lower than those of the untreated soils. It is known that the lower the C_c is, the stiffer the soil specimen will be. Thus, treated soil samples were stiffer than the untreated soil samples.

After the electro-kinetic treatment, Ca-PW-CL system had the lowest Cc (i.e., 0.52), while PW-PW-CL system had the highest Cc (i.e., 0.742). Ca-PW-CL and Ca-PW-WF systems (i.e., Cc equal 0.52 and 0.50, respectively), which
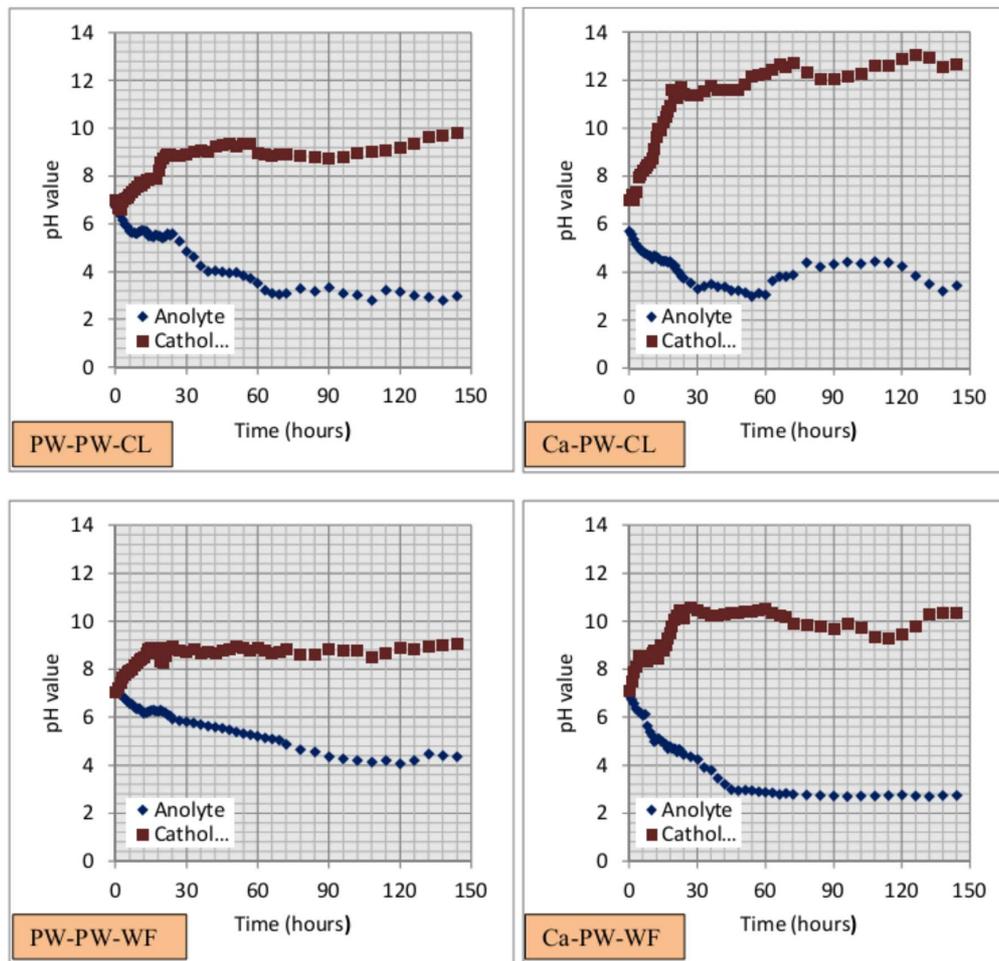
Figure 2: Distribution pH value of anolyte and catholyte after electro-kinetic treatment.

Table 2: Atterberg limit of soil after electro-kinetic treatment.

Atterberg limit	Initial	PW-PW-CL	Ca-PW-CL	PW-PW-WF	Ca-PW-WF	Average
Liquid Limit (LL), %	93.68	85.76	86.14	83.55	79.72	83.79
Plastic Limit (PL), %	28.92	30.80	25.22	29.40	26.44	27.97
Plasticity Index (PI)	64.76	54.96	60.92	54.14	53.28	55.83
Natural Water Content (wN), %	50.64	81.90	80.78	82.28	83.99	82.24
Liquidity Index (LI)	0.34	0.93	0.91	0.98	1.08	0.98

Table 3: Compression index of treated soils.

System	C_c	P_o (kg/cm^2)	e_o
PW-PW-CL	0.742	0.031	1.787
Ca-PW-CL	0.52	0.03	2.181
PW-PW-WF	0.55	0.03	2.101
Ca-PW-WF	0.50	0.30	2.107

treated with calcium chloride, had lower Cc than PW-PW-CL and PW-PW-WF systems (i.e., Cc equal 0.742 and 0.55, respectively), which treated with only pure water. The resulta indicate that soils treated with calcium chloride are stiffer than untreated soils. In the other case, Cc of the PW-PW-WF and Ca-PW-WF systems were lower than PW-PW-CL and Ca-PW-CL systems, respectively. Thus, soil samples treated under the flow water condition were stiffer than those under the no-flow condition were.

Undrained shear strength of treated soil

Undrained shear strength Cu of soil depends on the water content (Rustamaji ,2007). The higher water content, the lower undrained shear strength. Schofield and Wroth (1978; after Rustamaji, 2007) proposed that for remolded soil, the undrained shear strength, Cu, and the liquidity index, LI, are correlated by

$$C_u = 170\, e^{-4.6LI} \qquad (4)$$

The curve for variation of C_u with LI is approximately a straight line, which is assumed as a straight line with the undrained shear strength distance about 100 times, from Cu approximately 1.7 (i.e, LI equal 1) to 170 (i.e, LI equal 0). This straight line performs for almost normally remolded soil (Figure 4). According to Rustamaji (2007), when the distribution of treated undrained shear strength fall on the straight line, it means that the treated soil was altered by a change in water content, thus the increase is due to electro-osmotic strengthening. When treated strength distribution falls on the left, below the straight line, it means that no strengthening was achieved. And when treated
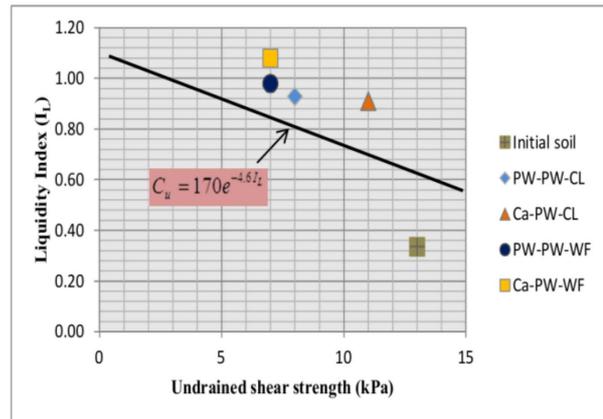

Figure 4: Undrained shear strength distribution of untreated and treated soil.

strength falls on the right, above the straight line, it means that strengthening was achieved after treatment. As the results, the distribution of undrained shear strength of soil sample is on Figure 4. Distribution of untreated soil sample is the only one below the straight line. It mean that the untreated soil might be very weak or weaker the normal standard for remolded soil. On the other hand, all treated soils are above the straight line suggesting that the treated soils are stronger than the untreated soil.

For further analysis of strengthening degree of the treated soils, in suggestion of researcher, percentage of strength increasing can be evaluated by following equation:

$$I_{USS}(\%) = \frac{C_u - C_u^*}{C_u^*} \qquad (5)$$

where

I_{USS} (%): increase of undrained shear strength

C_u (kPa): the undrained shear strength measured after treatment.

C_u^* (kPa): the undrained shear strength evaluated by equation (4)

The increase in the undrained shear strength of treated soils is shown Figure 5. The increase in the undrained shear strength of Ca-PW-WF system is the highest (i.e., approximately 556% as compared with untreated soil or 492% as compared with normally remolded soil). Greater increase of undrained shear strength
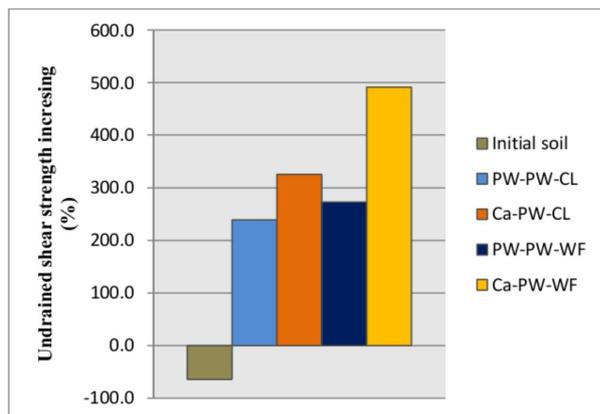
Figure 5: Distribution of undrained shear strength increasing.

was found in the treated soils using calcium chloride (i.e, Ca-PW-CL system, 394%, and Ca-PW-WF system, 556%). On the other hand, the treated soils under water flow condition (i.e, PW-PW-WF system, 338% and Ca-PW-WF, 556%) had degree of increase in strength greater than the treated soils under no-flow condition (i.e, PW-PW-CL system, 304%, and Ca-PW-CL, 394%). These results suggested that electro-kinetic treatment using calcium chloride was effective in strengthening expansive soil more than that using pure water. Besides, small flow of pure water is also an advantage on increasing undrained shear strength of treated soil. Flowing water carries the injected ions into the soil pores increasing the possibility of cation exchange.

Mineralogical composition of treated soil

In order to identify the mineralogical compositions and new crystal of the treated soil, X-ray diffraction (XRD) analyses were conducted. Table 4 summarizes the results of XRD analyses of the four treated soil samples. The results of XRD analyses show that no change in mineralogical composition between untreated and treated soil. The main clay minerals of the soil samples are montmorillonite. It suggest that XRD couldn't detect any new crystalline structure in the treated soils. This may be due to the low concentration of new crystalline or the resolution of X-ray diffraction instrument which may be insufficient to detect very small sized

single particles. Although the Scanning electron microscope (SEM) or petrography analysis could detect any new crystalline with a lower 5% concentration, clay particles are too small for optical crystallographic methods to be applied. Therefore, XRD has long been a mainstay in the identification of clay-sized minerals in soils (Harris and White, 2007).

The effect of electro-kinetic treatment on environment

Water filled in the compartments A and B simulates the influence of ground water when electro-kinetic treatment is applied to the soil in the field. The water of compartment A and B could be change its mechanism due to effect of the electro-kinetic treatment. Surrounding water before treatment is neutral with pH value approximately 7. After treatment, surrounding water of PW-PW-CL and Ca-PW-CL systems became slightly acidic resulting in the pH value to decrease slightly. On the other case, PW-PW-WF and Ca-PW-WF systems became slightly alkaline due to increasing pH value.

Distribution of pH value of surrounding water is shown in Figure 6. The change in pH of the PW-PW-WF Ca-PW-WF system is greater than that of the PW-PW-CL and Ca-PW-CL system. It confirmed that the treated soils under flow water condition was effective on environmental water more than that the treated soils under no-flow condition. On the other hand, the change in pH of the Ca-PW-CL and Ca-PW-WF systems is greater than that of the PW-PW-CL and PW-PW-WF systems. This indicated that the treated soils using calcium chloride was effective on environmental water more than that the treated soils using pure water.

4 Conclusions

1. Electro-kinetic treatment changed the physical and mechanical properties of the soil samples, as follows:

   - Firstly, pH value of anolyte decreased over time while pH value of catholyte increased. On the other hand, pH value of catholyte when treated with

Table 4: X-Ray Diffraction analysis of untreated and treated soils.

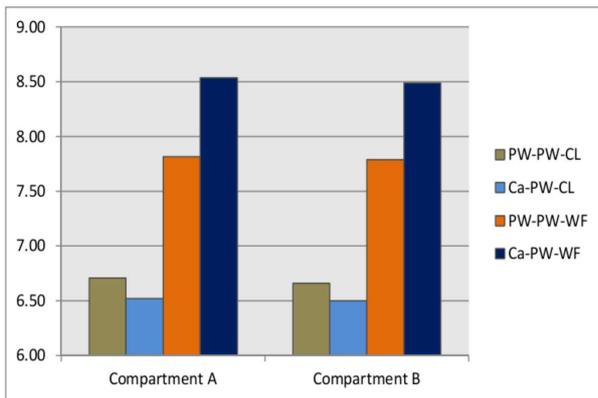|	Clay minerals identify	Other minerals identify
Initial soil	Montmorillonite, kaolin	Quartz, calcite
PW-PW-CL	Montmorillonite, kaolin	Quartz, calcite
Ca-PW-CL	Montmorillonite, kaolin	Quartz, calcite
PW-PW-WF	Montmorillonite, kaolin	Quartz, calcite
Ca-PW-WF	Montmorillonite, kaolin	Quartz, calcite

Figure 6: Distribution of pH value in compartment A and B after treatment.

calcium chloride was greater than when treated with pure water. pH value of catholyte of the treated soils under no-flow condition is greater than that under water flow condition.

- In general, LL and PI of all treated soil samples decreased. PL of the soil sample treated with calcium chloride decreased, while that of the soil samples treated with pure water increased slightly.

- All treated soils are stiffer than the untreated soil. Soil samples treated with calcium chloride under water flow condition were the stiffest. The treated soil samples using pure water and under no-flow were less stiff than the others.

2. The undrained shear strengths of the soil samples increased after the treatment. Undrained shear strength of the soil samples treated using calcium chloride under

water flow condition increased significantly.

3. There is no different in the mineralogical composition of the untreated soil and treated soils observed in the XRD analyses.

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