

## Improvement of Engineering Properties of Residual Soil of Tuff Breccia by Electro-Kinetic Method

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**ABSTRACT.** This paper presents the results of an experimental study that was conducted to improve engineering properties of residual soil of tuff breccia by applying the electro-kinetic method. The soil samples were taken from a slope in a high susceptible landslide area in the Kulon Progo, Yogyakarta, Indonesia. The electro-kinetic experiments were conducted using a clear glass tank of 60 cm × 30 cm × 30 cm size, a 13 V power pack to supply the voltage, and aluminum electrodes. The results showed that the pH value of anolyte decreased while that of catholyte increased during the treatment. The Atterberg's limits of all soil samples decreased, while the shear strengths increased. XRD and SEM analyses indicated that there were no mineral changes after electro-kinetic experiments. However, the soil structure changed and became denser. The increased soil strength after electro-kinetic treatment would likely improve stability of natural slopes.

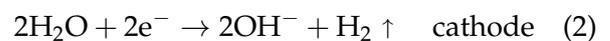
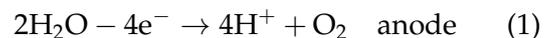
**Keywords:** Electro-kinetic · Soil improvement · Slope stability · Tuff breccia.

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### 1 INTRODUCTION

Electro-kinetic is defined as the physical-chemical transport of charge, action of charged particles, and effects of applied electric potentials on formation and fluid transport in porous media under an applied electric current (Alshwabkeh, 2001). Electro-kinetic phenomena results from the differential movement of two phases, which are solid and liquid phases, where the interface is an electrical double layer. There are four electro-kinetic phenomena; electro-osmosis, electro-migration, electro-phoresis and steaming potential. Referring to Rustamaji (2007), due to the electric field that is induced through adjacent electrodes, cations in the anolyte will move toward the cathode in the same direction due to both of electro osmosis and electro migration. On the other hand, the direction of anion transport is in the reverse direction of cation transport so that anion will move from the cathode to anode by the electro

migration mechanism. When anions are placed in anolyte, they will be transported by electro osmosis from the anode toward the cathode. In electro osmosis, electrolysis of water at the anode and the cathode produces oxygen and hydrogen, respectively, which can be represented by Equations (1) and (2), as follows:



The electrolysis reaction describes that acid will be generated at the anode side, while at the cathode side, alkaline will be produced (Equation (2)). Therefore, the pH value decreases at the anode but increases at the cathode. Propagation of acid and base fronts promote the dissolution of ions (or metal ions) near the anode and precipitation of the ions (or metal ions) near the cathode. The changes of physiochemical properties of the soil are different during electro-kinetic stabilization when admixtures are added to the soil, in which case the changes in behavior of the soil occurs through cementation or pozzolanic reactions (Nasim *et*

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*al.*, 2012). By the addition of an appropriate enhancement agent, such as lime or calcium chloride, 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 the 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. However, this type of reaction usually occurs when pH values of the soil solution are greater than seven. The soil improvement during electro-kinetic stabilization can occur due to the electro osmotic consolidation or electro-chemical changes such as pozzolanic reactions that lead to cementation of soil and the changes of mineral, resulting in the soil strengthening (Malekzadeh, 2016). In addition, the dissociation of calcium chloride and water results in increased concentrations of  $\text{Ca}^{2+}$  and  $\text{OH}^-$ , which accounts for the rise in pH value of the pore water. The strongly alkaline condition promotes the dissolution of silica ( $\text{SiO}_2$ ) and alumina ( $\text{Al}_2\text{O}_3$ ) from soil, which then gradually react with the  $\text{Ca}^{2+}$  ions, forming the secondary cementitious products, namely calcium silicate hydrate and calcium alumina hydrate, which hardened when cured to treat the soil (Justin and Robert, 2004).

Black and Wekman (2010) successfully stabilized a Victorian railway embankment in London by using electro-kinetic method. The embankment was 9 m high with  $22^\circ$  side slopes and was constructed by a mixture of London clay and brick fragments, overlying alluvium and terrace gravel. After soil treatments, the application of direct current, electrical potential was created and caused the water transported from cathode to anode. The difference of electrical potential (60–80 V) across the slope become the water to be drained away from cathode and lead to consolidation and increase in shear strength of the slope materials. The result

also indicated that 75 % increase in the factor of safety as a result of the electro-kinetic stabilization.

This research was conducted to improve engineering properties of residual soil of tuff breccia by applying the electro-kinetic method. The mineralogical properties of the residual soil prior to and after the electro-kinetic experiments were investigated to understand the factors causing the change of the soil engineering properties. Slope stability analyses were performed to assess the changes in the safety factors of natural slopes consisting of soils improved electro-kinetically.

## 2 MATERIAL AND METHODS

Soil samples used for the electro-kinetic experiments were taken from a landslide prone area in Samigaluh Sub-district, Kulon Progo Regency, Yogyakarta Special Region, Indonesia. According to Fauzian (2016), the groundwater table at the hillside of this area ranges from 1 to 3 m and on the top of the hill is  $>3$  m.

The electro-kinetic experiments were performed in a clear glass tank of 60 cm  $\times$  30 cm  $\times$  30 cm size, 13 V power pack to supply the voltage, and aluminum electrodes. Two sets of 16 cm high,  $34^\circ$  inclination soil slopes were constructed by placing the soil with compaction in the central compartment of the tank to achieve the same density of the natural soil. The angle of experimental slopes simulated the angle of natural soil slope in the field. To prevent the soil particles move to other sides, a cotton filter was used to separate the soil sample from four sides during the movement of water and chemical species. The compartments A and B were filled with tap water, which was used to simulate the groundwater condition in the field, while the two electrode compartments were filled with catholyte and anolyte solutions at a constant level (Figure 1). Two sets of electro-kinetic experiments were conducted where the catholyte compartments were filled with groundwater. In the first experiment, the anolyte compartment was filled groundwater, while in the second experiment the anolyte compartment was filled with calcium chloride, as a chemical solution (Table 1). Two 1 mm thick of aluminum plates were used as the cathode and anode. The experiments were performed by applying a constant

electric current DC power supply for the duration of the test. The value of pH at the anolyte and catholyte were measured every one hour for first 12 hours of the experiment, then every three hours until the following 3 days, after which the measurements were taken every 6 hours. Each of the electro-kinetic experiments were conducted approximately in 6 days. After each experiment, soil samples were taken at three different locations (i.e., near the anode, near the cathode, and in the middle of the soil slope) for tests of soil engineering and mineralogical properties. Soil engineering properties examined prior to and after the electro-kinetic experiments were Atterberg's limits and shear strength. Soil shear strength parameters (i.e., cohesion and internal friction) were determined by direct shear tests. To investigate the changes of soil fabric or occurring of new mineral due to the effect of cementation and precipitation behavior after electro-kinetic treatment, Scanning Electron Microscopy (SEM) and X-Ray Diffraction (XRD) analyses were conducted.

Slope stability analyses were subsequently performed to assess the changes in the safety factors (Fs) of natural slopes consisting of soils improved electro-kinetically. The slope stability analyses were performed using the ordinary method of slices.

### 3 RESULT AND DISCUSSION

XRD analyses showed that the residual soil contained several abundant minerals of montmorillonite, halloysite, kaolinite, K-feldspar, and quartz (Figure 2). The sheet-like and platy structures of kaolinite can be seen in the SEM micrograph of the untreated soil (Figure 3).

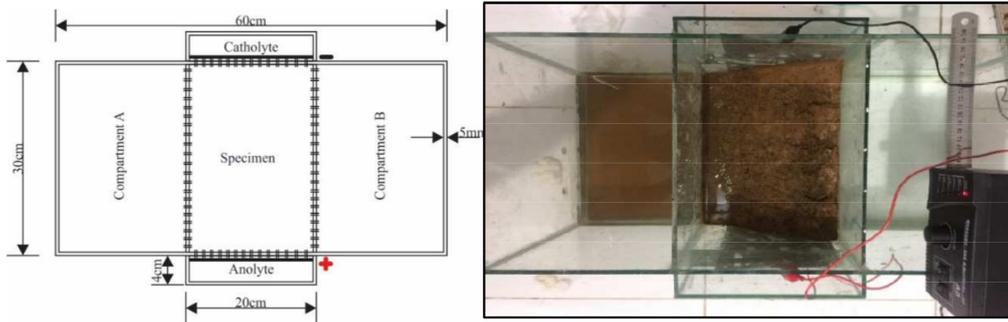
Table 2 and Table 3 show the Atterberg's limits of the soil samples prior and after the experiments of the Ca-Gw-Cl and Gw-Gw-Cl systems. It is shown that the Atterberg's limits of the soil samples after the electro-kinetic experiments decreased significantly. The electro-kinetic experiments also showed that the reduction of plastic and liquid limits of the soil samples in the Ca-Gw-Cl system was more significant than that of the Gw-Gw-Cl systems, although reduction of plasticity index of the soil samples in the Gw-Gw-Cl system was more significant than that of the Ca-Gw-Cl system. The addition of calcium chloride and groundwater

at the anode which caused decreasing in Atterberg's limit is due to dissolution of hydrogen and calcium ions and migrate from anode to cathode part.

Soil shear strength is governed by the internal friction angle and cohesion of soil particles. Direct shear strength tests showed that the natural residual soil in the research area typically had a relatively low internal friction angle ( $11^\circ$ ) but relatively high cohesion (24 kPa). The electro-kinetic experiments showed that the internal friction angles of the soil samples decreased, while the cohesions increased after the experiments (Table 4 and Table 5). The volume changing in soil particles and soil structure due to the electrochemical reaction in soil caused the decreasing of the internal friction angle and compaction of soil structure after the electro-kinetic experiments caused the increasing of cohesion of soil.

The addition of calcium ions at the anode part, which then migrated to the cathode, caused ion precipitation resulting in the changes in soil structure due to the electrochemical reaction in soil such as electrolysis, cation exchange and transportation of water. The changes of soil shear strength (Table 4 and Table 5) at the anode and the middle part of the soil were due to the cation exchange of calcium and hydroxide ions that reduced the thickness of double layer and the particles of the soil became densely packed each other. For Gw-Gw-Cl system, only natural groundwater was applied at both electrodes, therefore no significant increased soil shear strength occurred and only hydrogen ions and hydroxide ions were released in the electrolysis processes. In an alkaline environment, ion precipitation normally occurs and forms a cementing compound that bind the soil particles resulting in increase of soil shear strength under electric field. Under acidic environment, the abundance of hydrogen ions caused the changes of the pore fluid resulting in the changes of soil structure, although no cations, such as calcium, or other ions were introduced into the system (Mosavat, 2014). The results of XRD analyses prior to and after experiments shown in Table 6 and Table 7 indicate that there were no new minerals formed after the electro-kinetic experiments.

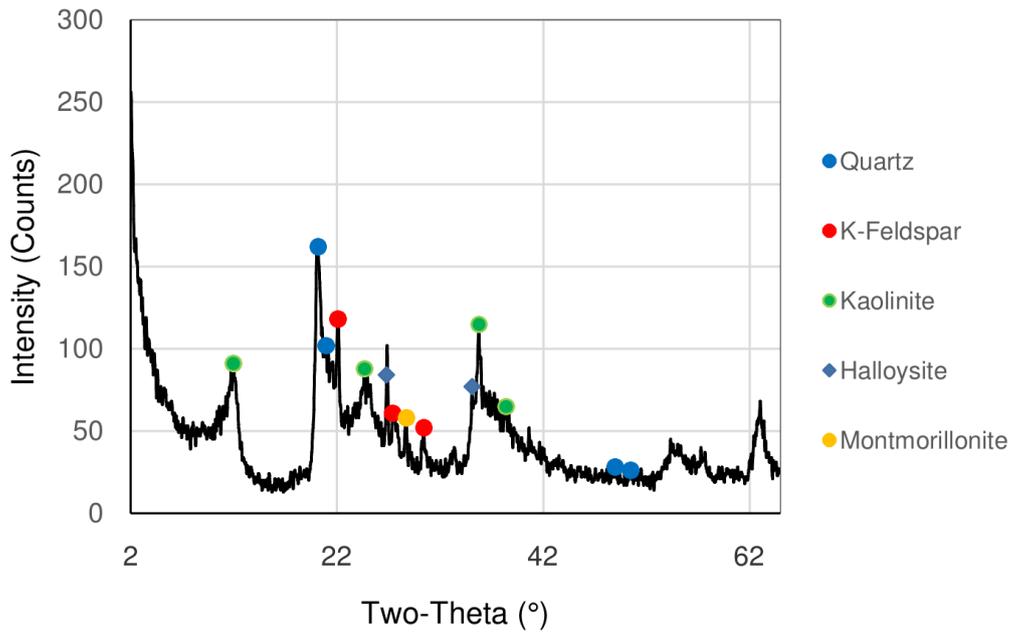
In the Ca-Gw-Cl system, the shear strength



**Figure 1.** Schematic diagram of the electro-kinetic set-up.

**Table 1.** Electro-kinetics experiments.

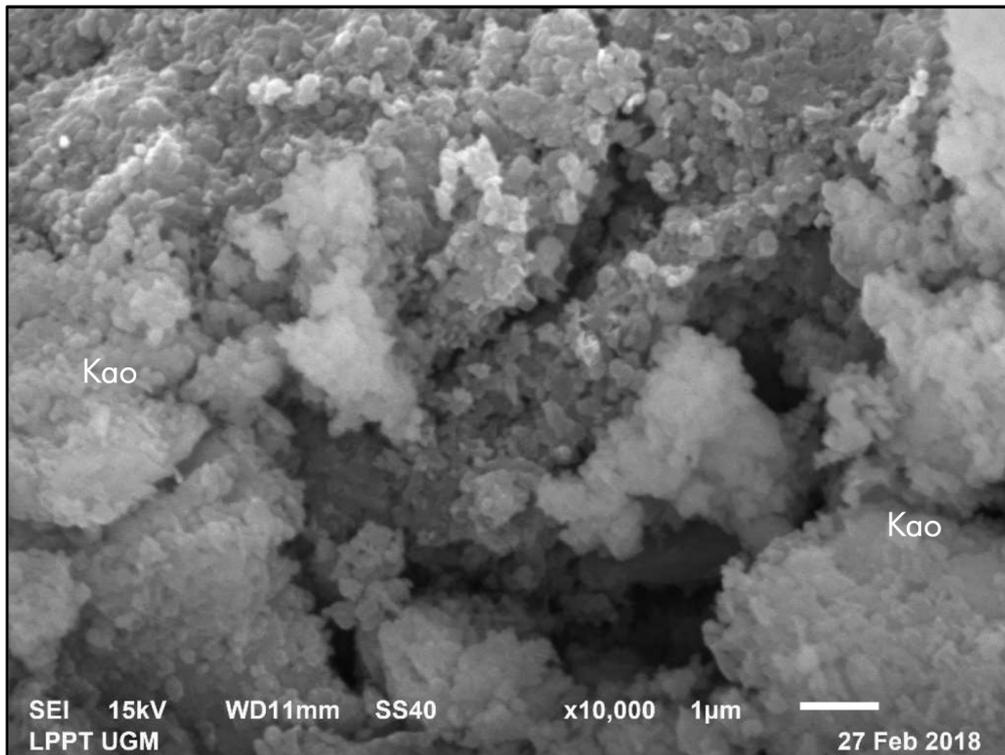
Anolyte	Catholyte	Water condition	System
Groundwater	Groundwater	Constant Level	Gw-Gw-Cl
Calcium Chloride	Groundwater	Constant Level	Ca-Gw-Cl



**Figure 2.** Diffractogram of the untreated soil sample.

**Table 2.** Atterberg's limits of the soil samples in the Ca-Gw-Cl system.

Parameter	Untreated soil	Treated soil			
		Anode	Middle	Cathode	Average
Liquid Limit (%)	56.11	41.00	37.72	38.47	39.07
Plastic Limit (%)	50.11	38.53	34.52	35.64	36.23
Plasticity Index (PI)	6.00	2.47	3.21	2.84	2.84



**Figure 3.** SEM micrograph of the untreated soil sample (Kao = kaolinite).

**Table 3.** Atterberg’s limits of the soil samples in the Gw-Gw-Cl system.

Parameter	Untreated soil	Treated soil			Average
		Anode	Middle	Cathode	
Liquid Limit (%)	56.11	45.21	39.19	39.73	41.38
Plastic Limit (%)	50.11	41.85	37.42	38.48	39.25
Plasticity Index (PI)	6	3.35	1.77	1.25	2.12

**Table 4.** Shear strength and shear strength parameters of the soil samples in the Ca-Gw-Cl system.

Parameter	Untreated soil	Treated soil			Average
		Anode	Middle	Cathode	
Cohesion (kPa)	24	59.6	56.07	64.1	59.92
Internal friction (°)	11	6.54	10.59	5.88	7.67
Shear Strength	34.42	66.21	66.85	70.04	67.7

**Table 5.** Shear strength and shear strength parameters of the soil samples in the Gw-Gw-Cl system.

Parameter	Untreated soil	Treated soil			Average
		Anode	Middle	Cathode	
Cohesion (kPa)	24	53.31	51.5	57.79	54.2
Internal friction (°)	11	5.21	7.85	7.06	6.71
Shear Strength	34.42	58.57	59.45	64.93	60.98

**Table 6.** Composition of minerals in the soil samples in the Ca-Gw-Cl system.

Ca-Gw-Cl System	Non-clay mineral	Clay mineral
Initial Soil	Quartz, K-feldspar	Halloysite, kaolinite, montmorillonite
Anode	Quartz, K-feldspar	Halloysite, kaolinite, montmorillonite
Middle	Quartz, K-feldspar	Halloysite, kaolinite, montmorillonite
Cathode	Quartz, K-feldspar	Halloysite, kaolinite, montmorillonite

**Table 7.** Composition of minerals in the soil samples in the Gw-Gw-Cl system.

Gw-Gw-Cl System	Non-clay mineral	Clay mineral
Initial Soil	Quartz, K-feldspar	Halloysite, kaolinite, montmorillonite
Anode	Quartz, K-feldspar	Halloysite, kaolinite, montmorillonite
Middle	Quartz, K-feldspar	Halloysite, kaolinite, montmorillonite
Cathode	Quartz, K-feldspar	Halloysite, kaolinite, montmorillonite

of the soil at the cathode was the greatest in this experiment. The mineral constituents of the soil samples did not change prior to and after the electro-kinetic experiment. However, the structures of the clay minerals were interconnected. [Figure 4](#), [Figure 5](#), and [Figure 6](#) show the images of soil fabrics at the anode, middle, and cathode parts, respectively, in the Ca-Gw-Cl system after the electro-kinetic experiment. At the anode, the clay minerals of kaolinite and montmorillonite appear to be interconnected each other leading to increase in shear strength of the soil samples as a product of cementation due to the cation exchange (electro-migration) and transportation of water (electro-osmosis). At the middle and cathode parts, the platy-structure clay minerals of kaolinite are seen closely connected each other and form aggregates of clay particles leading to an increased soil density. Precipitation of calcium compounds (CAH = Calcium Aluminum Hydrate) due to the pozzolanic reaction likely caused the microscopic structure of soil particles at the cathode to be denser than that at the anode and middle parts of the experimental setup as that gave the greatest shear strength increasing of the soil.

[Figure 7](#), [Figure 8](#), and [Figure 9](#) show micro structures of the soil samples at three different parts in the Gw-Gw-Cl system after the electro-kinetic experiment. The clay particles of montmorillonite appear to bind together causing a slight increased shear strength of soil sample at the anode part ([Figure 7](#)). At the middle and cathode parts, the platy-structure clay minerals of kaolinite are seen closely combined each

**Table 8.** Factor of safety of slopes consisting of untreated and treated soil samples.

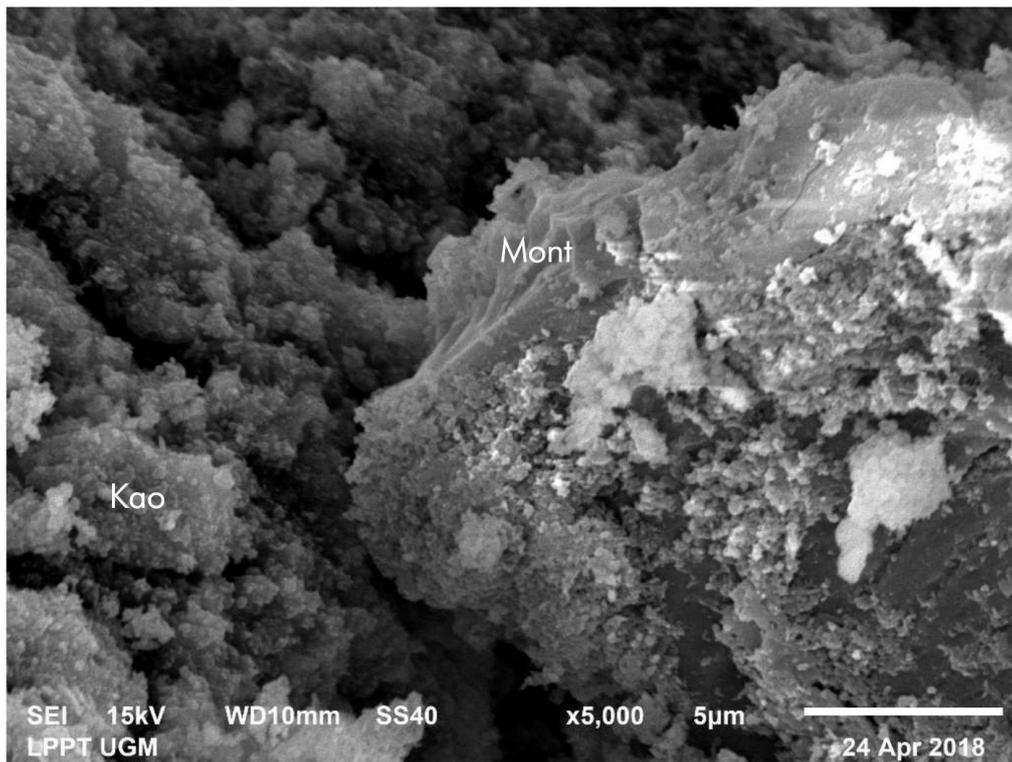
Types of sample	Factor of Safety (FS)
Untreated soil	1.75
Ca-Gw-Cl system	4.49
Gw-Gw-Cl system	4.07

other causing the soil samples to become denser and to increase the shear strength ([Figure 8](#) and [Figure 9](#)). It seems that the groundwater also increased slightly the shear strength of the soil samples under acidic environment due to abundance release of hydrogen ions at the anode and middle parts. At the cathode, precipitation of cations always occurs under the high alkaline environment, leading to the change in the soil structure and increase in the shear strength.

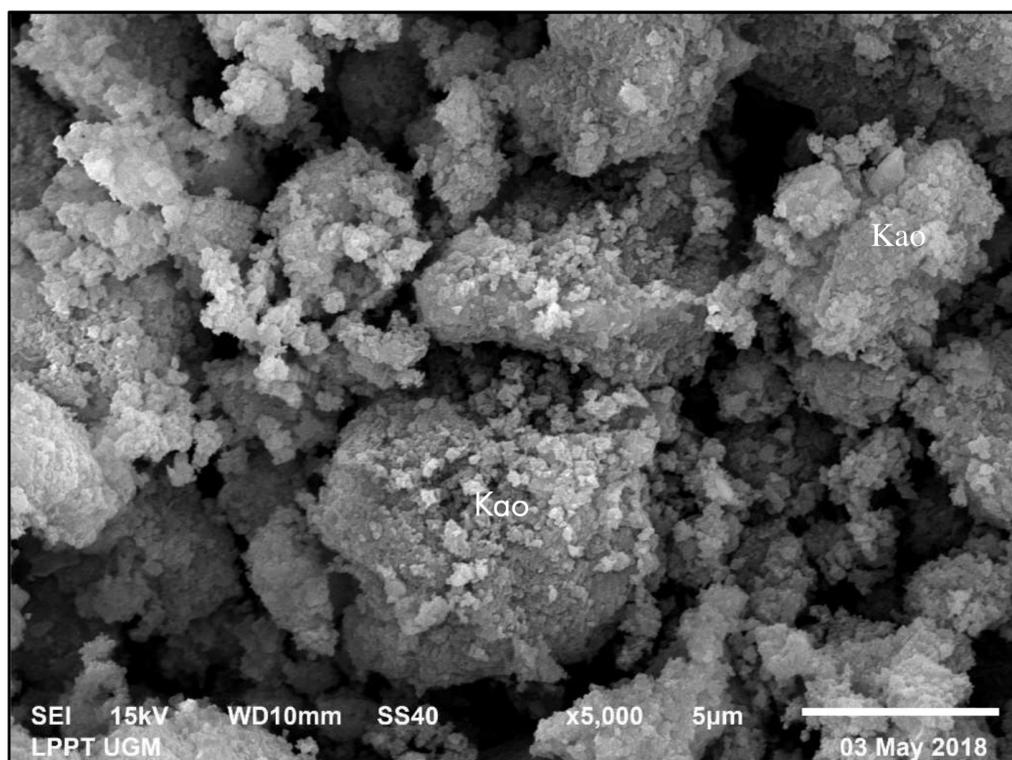
Results of the slope stability analyses are presented in [Table 8](#). It is shown that safety factors of the slopes increase, particularly after the electro-kinetic treatment with using calcium chloride solution. The increased soil strength after electro-kinetic treatment would likely improve stability of natural slopes.

#### 4 CONCLUSION

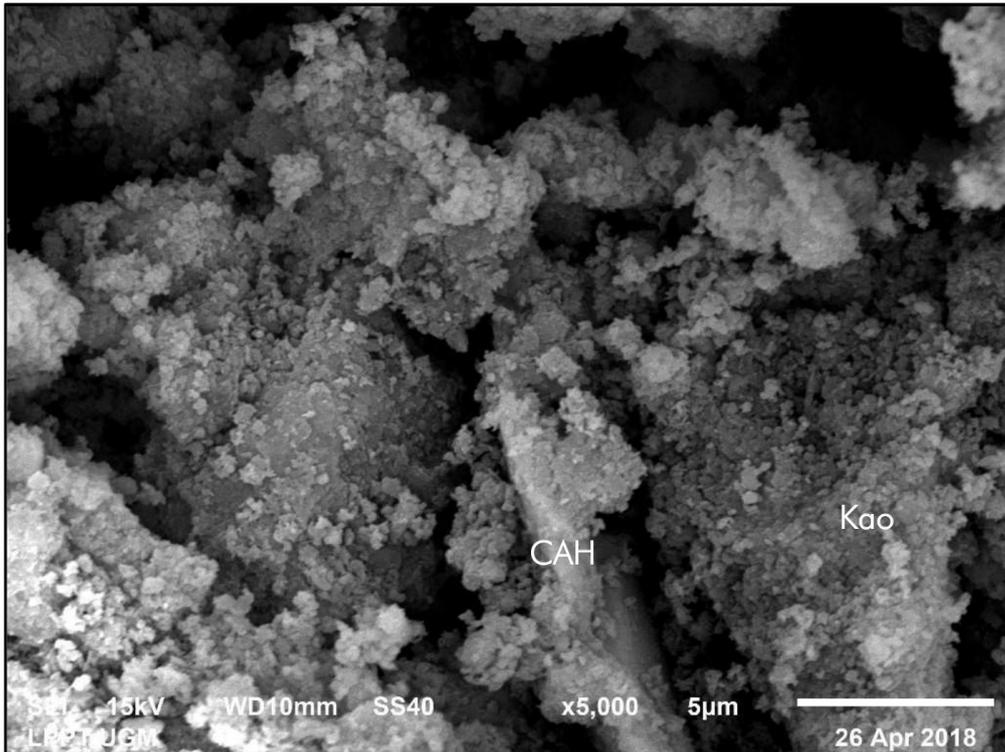
In this research, electro-kinetic experiments were conducted to improve the engineering properties of residual soil of tuff breccia collected in Kulon Progo, Yogyakarta, Indonesia. The results showed that the pH value of anolyte decreased while that of catholyte increased during the treatment. The Atterberg's limits of all soil samples decreased, while the shear



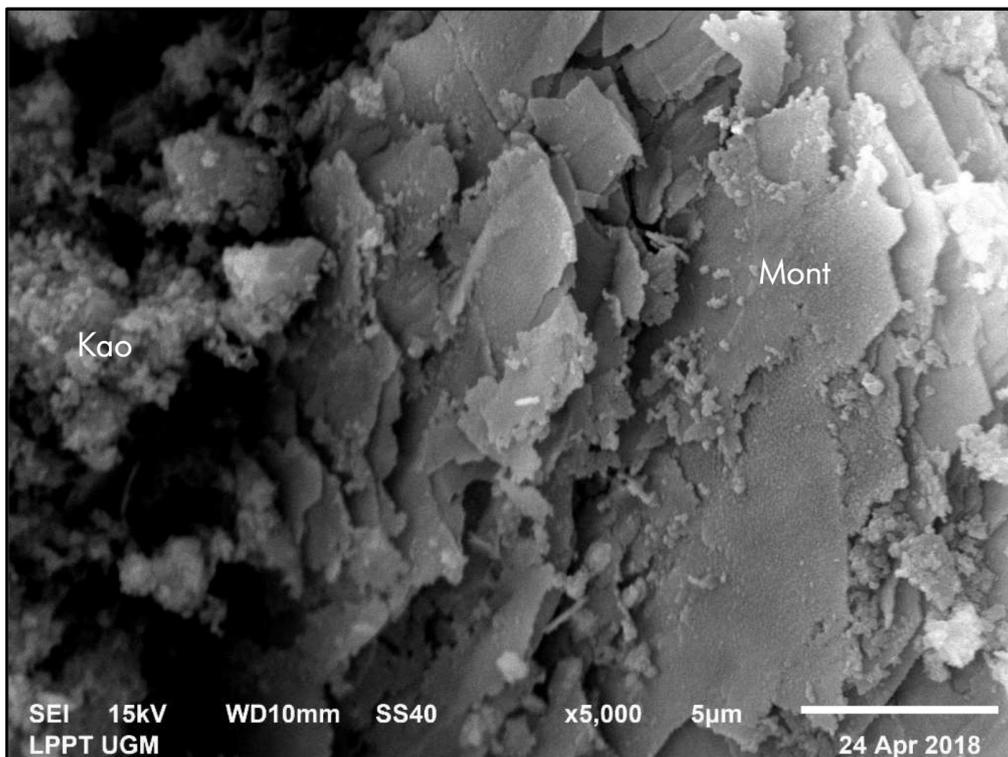
**Figure 4.** SEM micrograph of the soil sample in the Ca-Gw-Cl system at the anode part (Kao = kaolinite, Mont = montmorillonite).



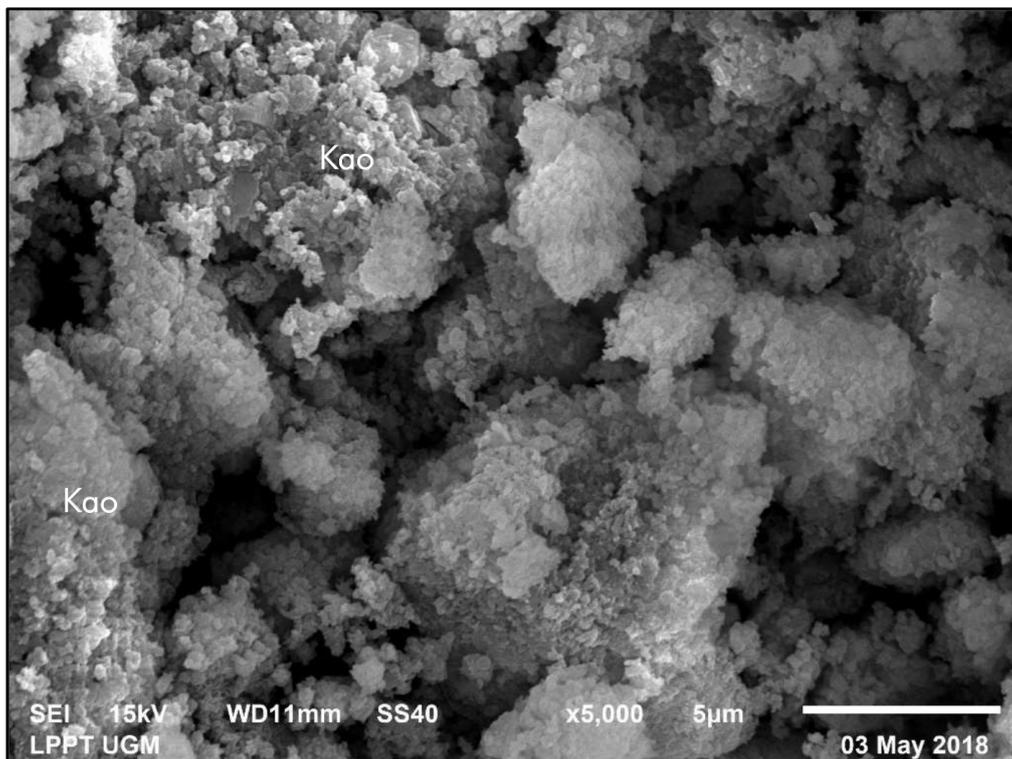
**Figure 5.** SEM micrograph of the soil sample in the Ca-Gw-Cl system at the middle part (Kao = kaolinite).



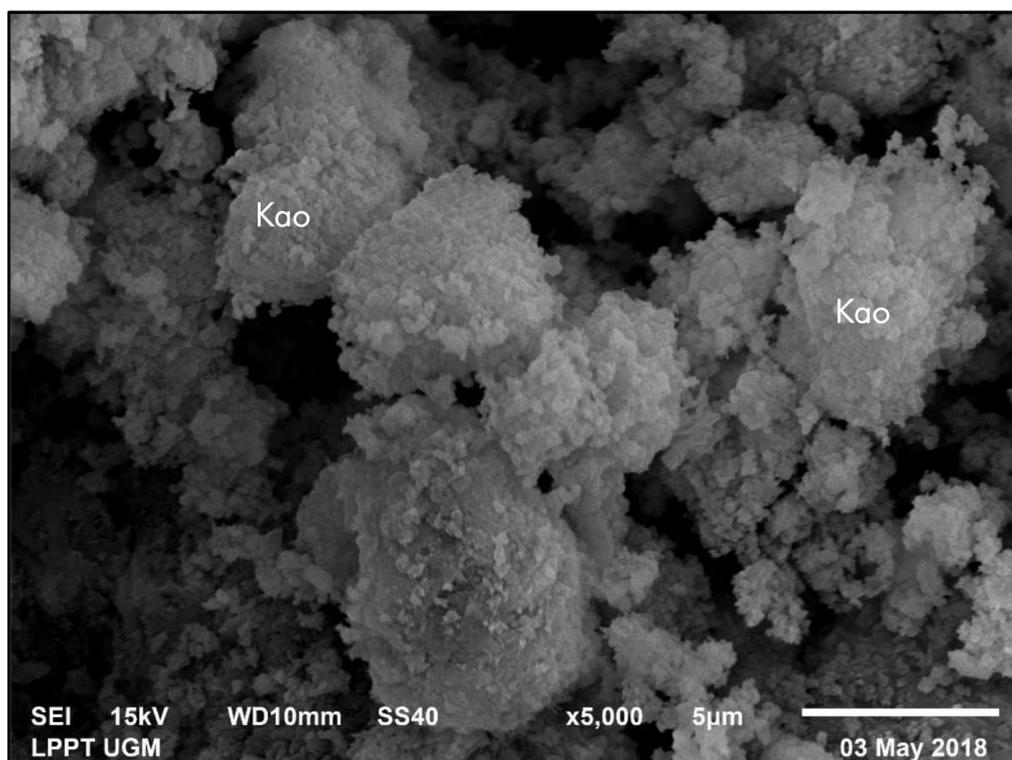
**Figure 6.** SEM micrograph of the soil sample in the Ca-Gw-Cl system at the cathode part (Kao = kaolinite, CAH = calcium aluminum hydrate).



**Figure 7.** SEM micrograph of the soil sample in the Gw-Gw-Cl system at the anode part (Kao = kaolinite, Mont = montmorillonite).



**Figure 8.** SEM micrograph of the soil sample in the Gw-Gw-Cl system at the middle part (Kao = kaolinite).



**Figure 9.** SEM micrograph of the soil sample in the Gw-Gw-Cl system at the cathode part (Kao = kaolinite).

strengths increased. Both calcium chloride solution and natural groundwater increased the shear strength of the soil samples after the electro-kinetic experiments. However, calcium chloride was found to be more effective in increasing soil shear strength as compared to groundwater. XRD and SEM analyses indicated that there were no mineral changes after electro-kinetic experiments. However, the soil structure changed and became denser. The increased soil strength after electro-kinetic treatment would likely improve stability of natural slopes.

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