

*Full Length Research Paper*

# Using secondary additives to enhance the physicochemical properties of kaolinite

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The adsorptions of various electrolytes namely;  $\text{CH}_3\text{COONa}$ ,  $\text{H}_3\text{PO}_4$ ,  $\text{Na}_2\text{SiO}_3$ ,  $\text{Na}_2\text{CO}_3$ ,  $\text{CaCl}_2$ , and  $\text{Al}_2(\text{SO}_4)_3$ , onto kaolinite from aqueous solutions were investigated using zeta potential test. Based on zeta potential results, 36 different binders were designed using  $\text{Na}_2\text{SiO}_3$  as well as  $\text{H}_3\text{PO}_4$  as main stabilizers mixed with  $\text{CaCl}_2$  and  $\text{Al}_2(\text{SO}_4)_3$  as secondary additives at various electrolytes. Moreover, unconfined compressive strength (UCS) was used to find the undrained shear strength (USS) of treated kaolinite. From the experimental results, (i) pH strongly alters the zeta potential of kaolinite; (ii) The zeta potential of the kaolinite soils varied from 204.6 to -41.9 mV, based on the used chemical reagents as well as their concentration; (iii) Some of the electrolytes are able to change the interface charge from negative to positive for kaolinite; (iv) thicker diffuse double layer (EDL) as well as higher pH at the PZC resulted from the greater electrolyte concentration. Based on the results of zeta potential and pH observed from using different cationic species, those PZC which are more close to the soil pH are more susceptible to be chosen as the best reagent to stabilizing soil. Also, batch test results clearly showed the importance of using both  $\text{CaCl}_2$  and  $\text{Al}_2(\text{SO}_4)_3$  electrolytes as secondary additives in EK injection systems.

**Key words:** Electrical double layer (EDL), kaolinite, zeta potential, point of zero charge (PZC).

## INTRODUCTION

Interaction of mineral particles with organic and inorganic compounds is deeply dependent on environmental characteristics such as pH, concentration of electrolytes and temperature, as well as surface charge properties, mineralogical, and used chemical species (Bear, 1965). Kaolinite is known as a 1:1 dioctahedralaluminosilicate which has two different basal cleavage faces (Mitchell and Soga, 2005). One basal surface consists of an octahedral gibbsite ( $\text{Al}(\text{OH})_3$ ) sheet. The other basal face consists of a tetrahedral siloxane surface of very inert – Si–O–Si– links. Theoretically, both these surfaces are electrically neutral. At the edges of a 1:1 layer, broken bonds occur due to the disruption of the structure, which are accommodated as -OH groups. These edges are approximately estimated to occupy 10% of the whole kaolinite surface (Stevenson, 1994; Nalan et al., 2006).

The kaolinite surface has a complex chemistry because of the existence of these different sites on the basal edges and faces. Also, kaolinite is a mineral which has a wide variety of applications in industry (Yu, 1997; Huat, 2004; Mitchell and Soga, 2005). It is used as a functional additive in polymers and as an extender in water-based paints and ink and is also a major component of ceramics (Edil et al., 1992; Fang and Daniels, 2006). Kaolinite is also an inexpensive additive that can improve the material properties in which it is dispersed provided that a stable dispersion is formed (Khalili et al., 1999; Das, 2008). Moreover, kaolinite mineral particle's surface is including negative structural charge. Such negatively charged particles can develop new invented injecting methods such as Electro-ion migration (EM) as well as Electro-osmosis (EO) injection (Casagrande, 1983). Rather than relying on soil permeability (which for the targeted soil is about  $10^{-7}$  cm/s), both EO and EM methods use applied electrical potential in order to induce fluid movement through soft soils as well as ion migration

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**Table 1.** Physico-chemical characteristics of kaolinite soil.

Parameter	Property
Color	Yellow
Water content (%)	18
Liquid Limit (LL, %)	37
Soil pH	5.8
Specific surface area (BET m <sup>2</sup> /g)	16
CEC (meq/100g soil)	8
Organic matter content (%)	1.8
USS (kPa)	15
Specific gravity (G <sub>s</sub> )	2.55
Optimum water content (W <sub>opt</sub> )	25
Maximum dry unit weight	14.77

**Table 2.** Chemical composition of used kaolinite soil.

Constituent	Percentage present
SiO <sub>2</sub>	66.4
Al <sub>2</sub> O <sub>3</sub>	28.65
Na <sub>2</sub> O	0.76
K <sub>2</sub> O	1.46
CaO	<0.64
Fe <sub>2</sub> O <sub>3</sub>	<0.34
MgO	<0.25
LoI	4.3

LoI: loss of ignition.

of charged grouting agents, respectively (Alshawabkeh and Sheahan, 2003; Kazemian et al., 2011a and b).

A major advantage of EK remediation is that transport by EO and also EM is significant in soils with low hydraulic conductivity. Another advantage could be the possibility of developing a relatively uniform flow transport in a porous media. Although ion migration rates are lower in clays than in sand, the differences are not as considerable when compared with transport by hydraulic gradient, where the permeability of sandy soils in order of magnitude is higher than clayey soils (Alshawabkeh, 2009; Asadi et al., 2011a, b). Thus hydraulic gradients are ineffective in contaminants removal from heterogeneous soils due to limited transport in fine soils.

In any heterogeneous soil, using ionic migration can cause a relatively uniform transport. However, transport in soils is more difficult to assess when accounting for the ion migration and/or reactivity of contaminants (Agiri and Akaranta, 2009).

On the other hand, coagulation and flotation as well as colloidal dispersion mechanism could be a good example. Selecting suitable flotation reagents requires understanding the effect of different types of collector adsorption on soil colloidal particles, their minerals and activation mechanisms (Mitchell and Soga, 2005; Fang

and Daniels, 2006; Das, 2008). As for coagulation, an important issue in most suspension separation processes such as waste water treatment systems is to find zeta potential behaviors of solid/liquid solution and their PZC as well (Stevenson, 1994; Acar and Alshawabkeh, 1996; Yu, 1997; Asadi et al., 2010; Moayedi et al., 2011a).

Also, using various electrolytes causes significant change in EDL of kaolinite colloidal particles. This will eventually affect the USS and its hydraulic conductivity as well (Acar et al., 1997; Asadi et al., 2010). The main objective of this research was to study physicochemical properties of treated kaolinite with 36 different binders. Results provided in this study can improve injecting stabilizers such as Na<sub>2</sub>SiO<sub>3</sub> and H<sub>3</sub>PO<sub>4</sub> through extremely soft and semi permeable soils applying EK methods.

## MATERIALS AND METHODS

### Test materials

Kaolinite was collected as a hand specimen from a deposit nearby Serdang-Malaysia. It has a Cation Exchange Capacity (CEC) of 8 meq. per 100 g, compared to or highly organic soil like peat between 60 to 120 meq. per 100 g or even other minerals such as montmorillonite with 80 to 100 meq. per 100 g, is not considerable. That means small amounts of organic matter or montmorillonite particles can act as a stabilizing agent to the kaolinite suspension by having a peptizing effect (Asadi et al., 2009). Physicochemical properties of kaolinite used in the present research are shown in Table 1. Moreover, the report was prepared in accordance with BSI 1377-7-5:1990. Chemical composition of kaolinite was also analyzed using x-ray fluorescence (XRF) spectrometer (Table 2).

### Zeta potential measurements

Zeta potential can provide valuable information about particle and surface charges in chemical species solutions. To determine the zeta potential of the kaolinite colloids, different tests were carried out using Zeta Meter 3.0 model which is able to conduct electrophoretic mobility measurements to find zeta potential (Zeta-Meter guideline) Figure 1.

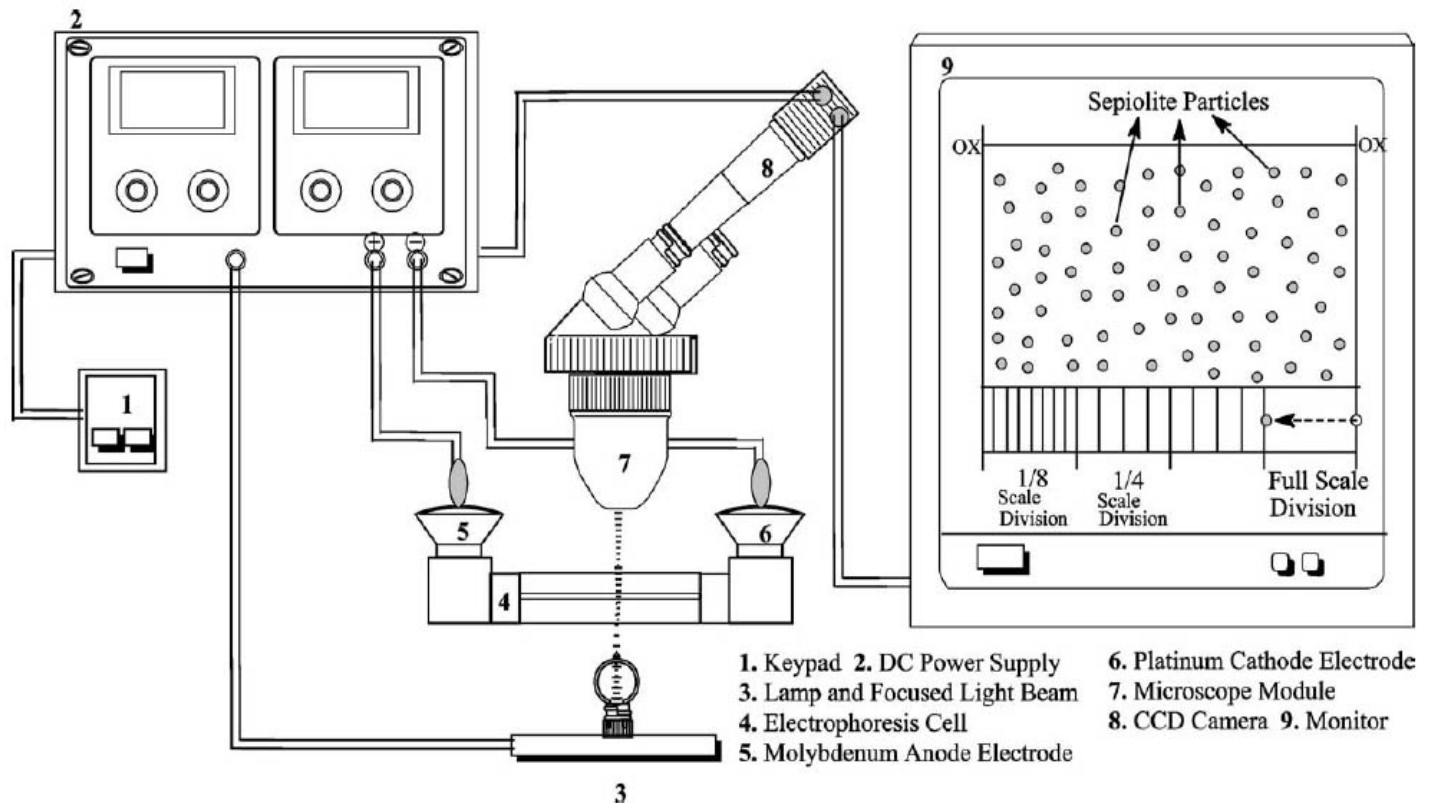


Figure 1. Zeta Meter 3.0., General schematic (Zeta meter manual).

### Preparation of samples for zeta potential test

In this research, zeta potential measurements were carried out based on immersing 0.1 g/L concentration of solid particles in liquid. A magnet stirrer was used to mix solid particles through the electrolyte solution. The kaolinite suspension was stirred until a constant pH was found. Before and after each zeta potential measurement, the pH was measured and if any changes occurred, the last record was considered. Moreover, standard deviation was used for zeta potential measurement to determine reliability of the recorded zeta potential.

The standard deviation was less than 2mV for each measurement, which is calculated by the zeta meter instrument automatically. The zeta potential of at least 15 particles was determined for each test and finally their average was considered. The room temperature was about  $24 \pm 2.5^\circ\text{C}$ . Further details of zeta potential measurements are described by Hunter (1981), Asadi et al. (2009) and Moayedi et al. (2011b).

### Unconfined Compressive Strength test (UCS)

A series of Unconfined Compressive Strength (UCS), on treated kaolinite soil using  $\text{Na}_2\text{SiO}_3$  and  $\text{H}_3\text{PO}_4$  as main stabilizers and  $\text{CaCl}_2$  and  $\text{Al}_2(\text{SO}_4)_3$  as secondary additives were carried out to not only find the effect of secondary additives on USS of treated soil but also exploring its relation corresponding to the EDL obtained from zeta potential results. UCSs were conducted as Phase II by mixing soil samples with 36 different binders (Table 3). It is noteworthy that the curing system and the mixing procedure used in this study research were that adopted in the Euro Soil Stab Project (EuroSoilStab Manual, 2002).

## RESULTS AND DISCUSSION

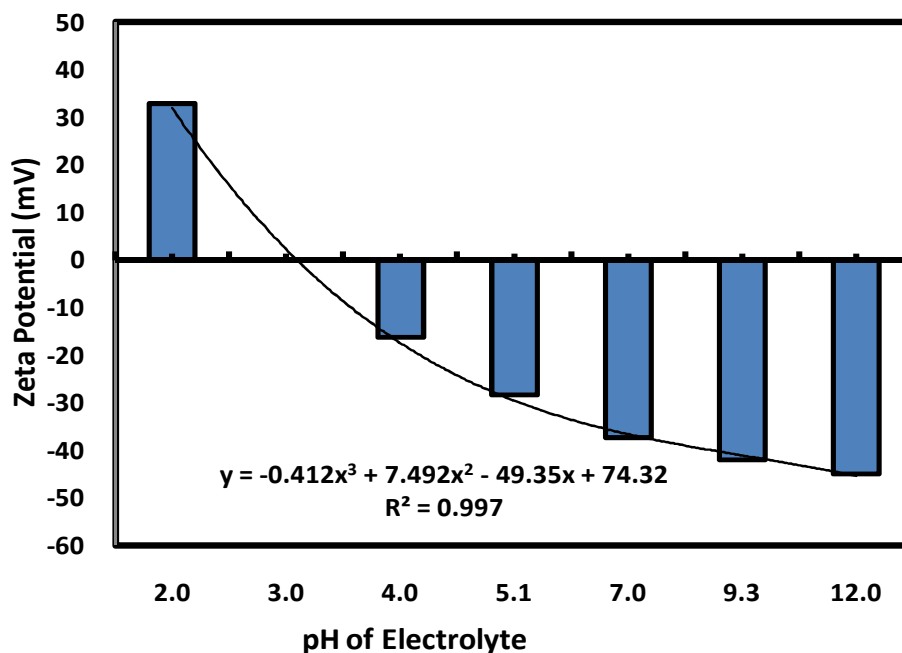
### Effect of electrolyte type on zeta potential of kaolinite

Zeta potential versus pH relationship for kaolinite is presented in Figure 2. The zeta potential of pure kaolinite soils varied from +32 mV at pH ~ 2 to -41 mV at pH ~ 12. Also, the zeta potential was found to be zero at pH ~3.3 (Figure 2). It can be seen that increasing pH caused zeta potential value to decrease (Figure 2).

The variations in zeta potential with pH were probably related to the nature of electrical energy field in kaolinite soil particles (Burnotte et al., 2004; Asadi et al., 2009). This might be considered as a generation of variable charge mechanism since the positive surface charge of kaolinite colloids increased with decreasing the suspension pH. However, due to the protonation of surface hydroxyl groups on kaolinite, their surface negative charges tend to decrease (Stevenson, 1994). Moreover, change in EDL thicknesses of colloids are related to their surface charges (Brunelle, 1980; Eykholt and Daniel, 1994; Agiri and Akaranta, 2009; Jumaat and Alam, 2011; Ahmed et al., 2010). For example, under acid conditions, kaolinite carries a net positive surface charge and in the alkaline part, they tend to carry a negative charge.

**Table 3.** Chemical compound of the designed binders.

Chemical	Used synonym	Molarity (mol/L)			
		Step 1	Step 2	Step 3	Step 4
Na <sub>2</sub> SiO <sub>3</sub>	N	0.1, 1, 3	0.1, 1, 3	0	0
H <sub>3</sub> PO <sub>4</sub>	H	0	0	0.1, 1, 3	0.1, 1, 3
CaCl <sub>2</sub>	C	0, 0.1, 1	0, 0.1, 1	0, 0.1, 1	0, 0.1, 1
Al <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub>	A	0	0.1	0	0.1

**Figure 2.** Zeta potential - pH relationship for pure kaolinite.

Figures 3 and 4 showed a zeta potential of kaolinite particles immersed in various electrolytes. Immersing kaolinite in CaCl<sub>2</sub> electrolyte caused an EDL of kaolinite colloids to increase with increasing molarities. It should be mentioned that there was no PZC for CaCl<sub>2</sub> suspension (Figure 3a). Also, the pH at a PZC of suspended colloids in Al<sub>2</sub>(SO<sub>4</sub>)<sub>3</sub> was 5.25, 6.90, and 8.90 according to electrolyte molarities of 0.001, 0.005, and 0.01 mol/l, respectively (Figure 3b). It is found that increasing Al<sub>2</sub>(SO<sub>4</sub>)<sub>3</sub> molarity causes a shift in pH at PZC towards the alkaline part. Na<sub>2</sub>CO<sub>3</sub> also resulted in higher EDL thickness with a negative sign which means Na<sub>2</sub>CO<sub>3</sub> can enhance EO flow injection from the cathode to the anode (Figure 3c).

Moreover, the zeta potential of kaolinite particles immersed in both Na<sub>2</sub>SiO<sub>3</sub>, and H<sub>3</sub>PO<sub>4</sub> is shown in Figure 4. As mentioned, these chemicals are used as the main stabilizer throughout this research. It can be seen that using Na<sub>2</sub>SiO<sub>3</sub> thickened the EDL of kaolinite colloidal particles (negative sign) and there is no PZC compared

with pure kaolinite (Figure 4a). However as for H<sub>3</sub>PO<sub>4</sub>, in high electrolyte concentration, zeta potential value reversed to the positive sign (Figure 4b).

### The influence of surface charge on EK

EK phenomena are greatly affected by edge faces since active hydroxyl sites are located on these planes. It is well known that the surface of a colloidal particle immersed in a chemical solution is always electrically charged (Mitchell and Soga, 2005). Three main mechanisms are responsible for the charging of the surface: (i) ion adsorption, due to which ionic charge is taken from the electrolyte solution to the surface. (ii) Surface dissociation, that is, departure of ions from the surface and their transfer to bulk electrolyte solution; (iii) isomorphic replacement of ions of the solid phase by others of a different charge, which is accompanied by sorption of electrons from the outside (Stevenson, 1994;

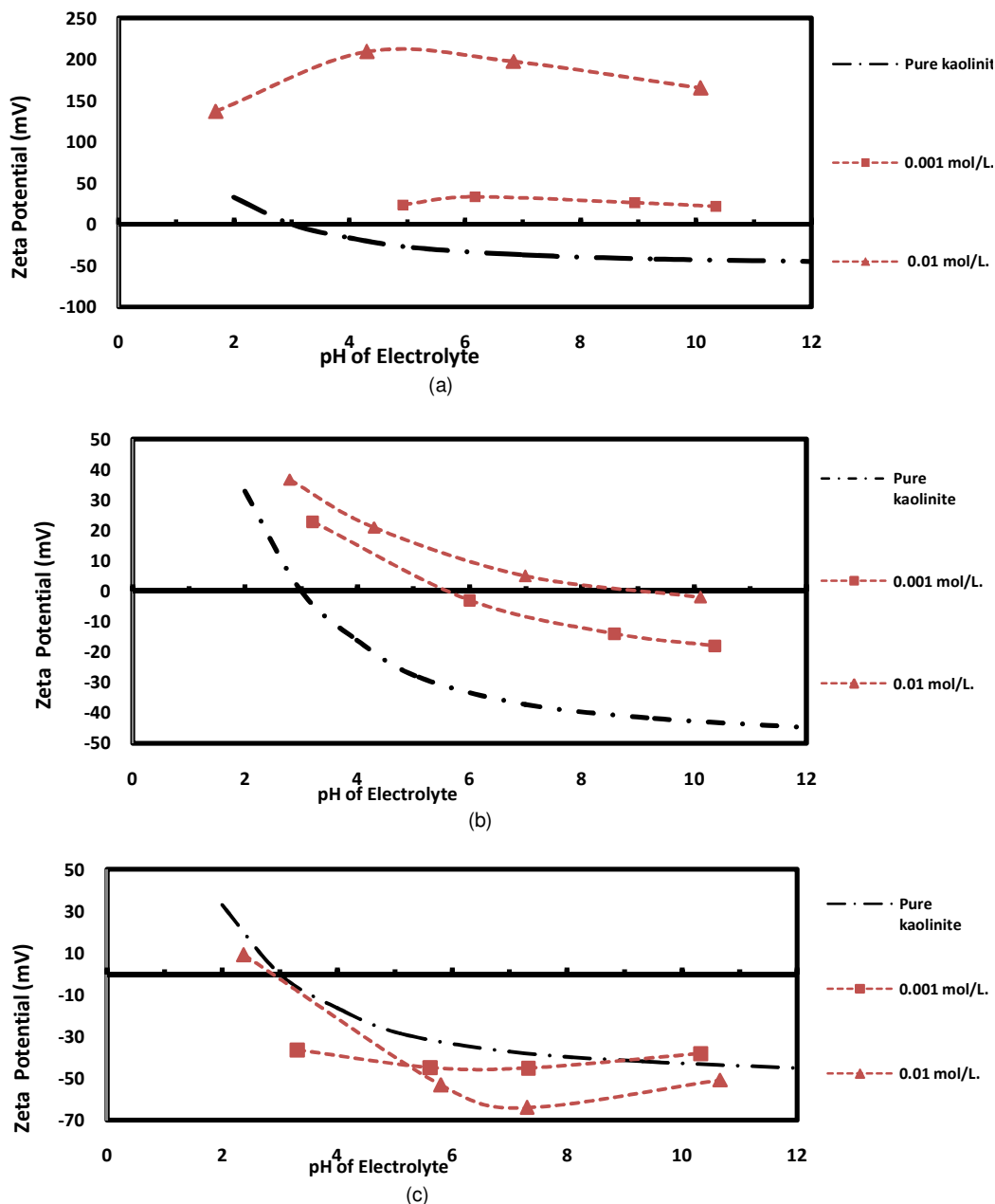


Figure 3. Zeta potential of suspended kaolinite immersed in; (a)  $\text{CaCl}_2$ , (b)  $\text{Al}_2(\text{SO}_4)_3$ , (c)  $\text{Na}_2\text{CO}_3$ .

Nalan et al., 2006; Lorenz, 1969).

The electrical field of charged colloidal particles attracts the ions of opposite sign and repels the ions of the same sign of the particle, originating the screening of the particles' charge by the free ions in the solution. Consequently, the whole system, i.e., the charged particle, together with its screening charge, reaches a state of electro-neutrality (PZC), which is characterized by the ionic charge screening of colloidal particle's surface charge and space separation of it (Lefebvre and Burnotte, 2002). The electro-neutral system includes spatially separated charges. The charge localized on the

colloid's particle surface and the screening charge localized in the adjacent electrolyte solution forms the EDL of the colloid particle (Stevenson, 1994; Hunter, 1981; Taha and Kabir, 2005). Due to the electro-neutrality state, kaolinite soil particles in soil water will not repel each other but try to aggregate and form larger particles. This effect in turn will contribute to an increase in soil permeability through the soils and tend to increase by increasing the flocculation process (Ozkan et al., 1999). In contrast, electro-negatively charged soil particles repel each other, resulting in dispersion and decrease soil permeability. Also, from those electrolytes

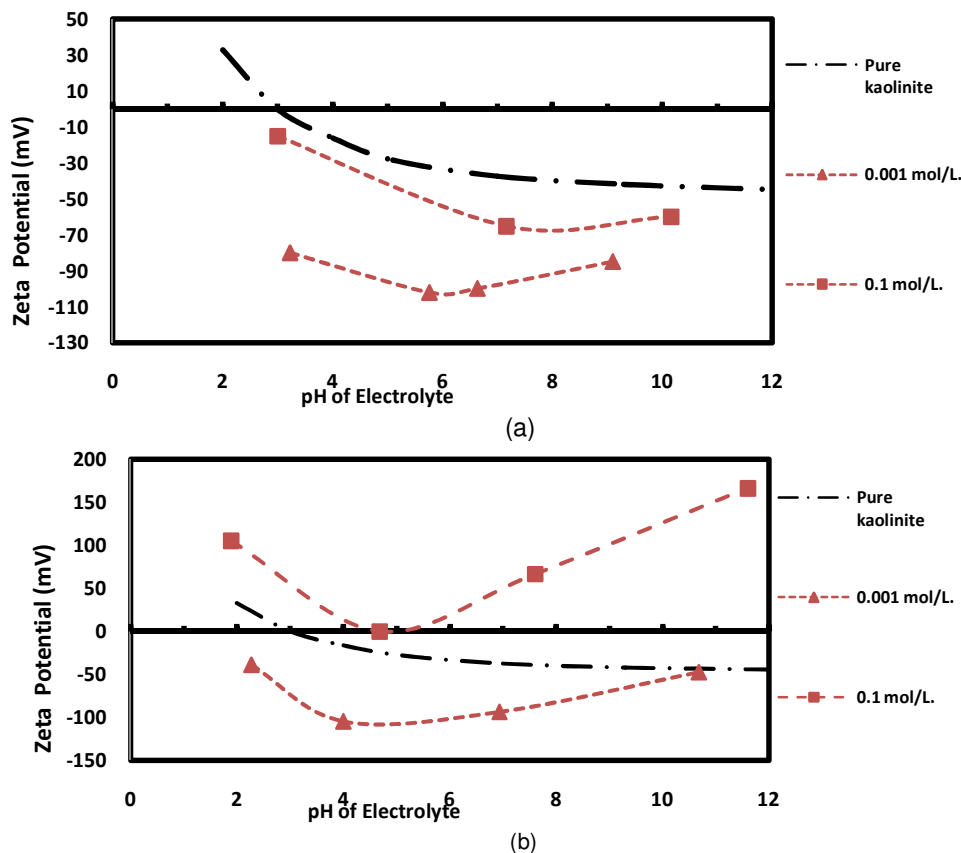


Figure 4. Zeta potential of suspended kaolinite immersed in (a)  $\text{Na}_2\text{SiO}_3$ , and (b)  $\text{H}_3\text{PO}_4$ .

which caused compression in EDL thickness, decreasing EO flow is expected. This means either less solution flow transporting or higher ion migration injection (Ou et al., 2009; Van, 1977).

#### Effect of electrolyte molarity on EDL

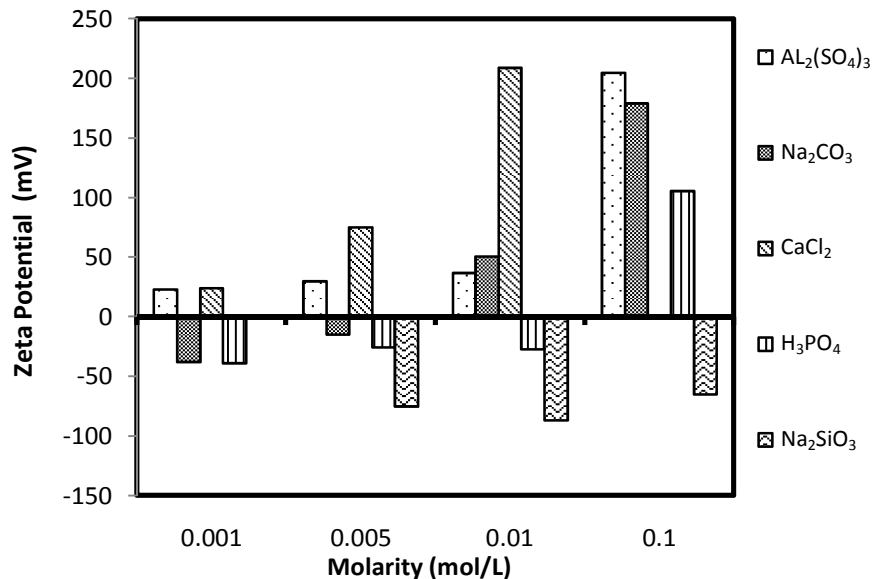
The variation of zeta potential with electrolyte concentration for  $\text{CH}_3\text{COONa}$ ,  $\text{H}_3\text{PO}_4$ ,  $\text{Na}_2\text{SiO}_2$ ,  $\text{Na}_2\text{CO}_3$ ,  $\text{CaCl}_2$ , and  $\text{Al}_2(\text{SO}_4)_3$ , onto kaolinite from aqueous solutions at the natural pH of the medium has been provided in Figure 5. The data clearly support the fact that the charge placed in a colloidal surface is affected by solution pH. Change in surface charge even at the natural electrolyte charge could be due to electrolyte type as well as electrolyte molarity, and their dissociation since all these parameters are in direct relation with chemical additives (Yu, 1997; Stevenson, 1994; Mathuriau and Chauvet, 2002). Zeta potential behavior of  $\text{CaCl}_2$  solution showed a peak value of 33.3, 130 and 209.2 mV at an electrolyte concentration of 0.001, 0.005 and 0.01 mol/L, respectively. Moreover, the higher molarities led to lower pH in their maximum values. For instance, for zeta potential of kaolinite particles immersed in  $\text{CaCl}_2$ , pH values corresponding to the maximum zeta potential were 6.18, 5 and 4.13 at 0.001, 0.005 and 0.01

electrolyte molarities, respectively (Figure 5). This could be due to changes in the dehydrated calcium ions concentration in the inner Helmholtz plane, ascribed variations in the dissolution rate (Mitchell and Soga, 2005).

Theories on EO suggest that decreasing the EDL decreases EO (Alshwabkeh and Sheahan, 2003; Mitchell and Soga, 2005). As for used kaolinite particles, higher electrolyte contents had more influence over increase of the natural zeta potential in comparison with reagents having less electrolyte content (Figure 5). Thus, the relationship between electrolyte concentration and zeta potential are not only based on electrolyte molarity contents, but also under influence of electrolytes as well as soil type.

#### Effect of electrolytes on specific conductivity

The specific conductivity concept is typically applied to the case of homogeneous electrolytes. Inside the charged pores, the potential and the ionic concentration vary from the charged surface to the bulk solution (Hunter, 1981; Lefebvre and Burnotte, 2002; Burnotte et al., 2004). Although, the specific conductivity titration curves of  $\text{Na}_2\text{CO}_3$  and  $\text{H}_3\text{PO}_4$  as well as the titration



**Figure 5.** Effect of electrolyte concentration on zeta potential of kaolinite in the natural pH of the electrolytes.

**Table 4.** Detailed experimental data for effects of pouring amendment addition to kaolinite.

Reagent	Molarity (mol/L)	Specific conductivity (micro S/cm)	pH	Av. Zeta potential (zeta potential) (mV)	Applied voltage (V)
$\text{Na}_2\text{SiO}_3$	0.001	146.5	6.6	0	100
	0.01	446	9.3	-86.94	100
$\text{H}_3\text{PO}_4$	0.001	823	2.4	-39.2	100
	0.01	1032	2.4	-27.38	100
$\text{Al}_2(\text{SO}_4)_3$	0.001	699	3.2	22.87	100
	0.01	2210	3.1	36.77	100
$\text{CaCl}_2$	0.001	360	4.9	23.9	100
	0.01	15640	4.3	209	50
$\text{Na}_2\text{CO}_3$	0.001	730	10	-38.07	100
	0.01	2220	11	50.69	100

curves of  $\text{Al}_2(\text{SO}_4)_3$  and  $\text{Na}_2\text{SiO}_3$  were similar,  $\text{CaCl}_2$  electrolyte was found to be a more conductive reagent (Table 4). As for secondary additives used in this research,  $\text{Al}_2(\text{SO}_4)_3$  showed lower specified molarities compared to  $\text{CaCl}_2$  indicating that  $\text{CaCl}_2$  is more susceptible to work as a secondary additive and it will present better injection (Figure 6). Previous studies also mentioned the importance of  $\text{CaCl}_2$  on EO flow of water through the clay (Ou et al., 2009; Chien et al., 2009). Based on Smoluchowski's Equation, higher specific conductivity significantly caused zeta potential values to increase (Smoluchowski, 1921).

On the other hand, the zeta potential of kaolinite

particles immersed in  $\text{Al}_2(\text{SO}_4)_3$  solution at electrolyte concentrations of 0.001, 0.005, 0.01 and 0.1 mol/L were 22.87, 29.7, 36.77 and 204.6 mV respectively (Figure 5), in their natural pH which were 3.2, 3.13, 3.05 and 2.8 respectively. Considering the zeta potential sign, observed results clearly show that electrolyte molarities significantly increase positive zeta potential values in acidic part as well as negative values in alkaline part which means thickening of the EDL of colloidal particles. It is noteworthy that the zeta potential of kaolinite colloids immersed in  $\text{CaCl}_2$ , corresponding 0.1 mol/L and/or more, using the current von Smoluchowski theory (Smoluchowski, 1921) could not be calculated.

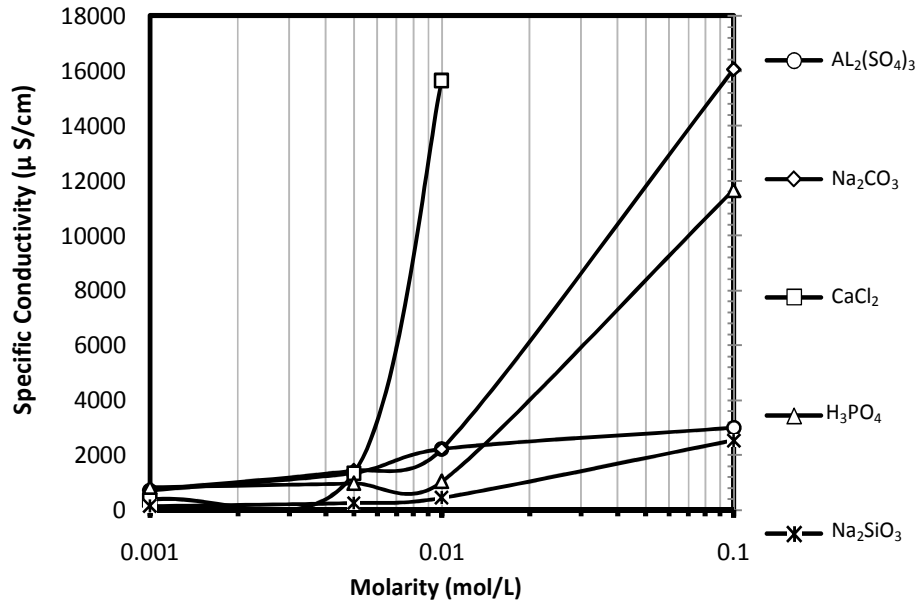


Figure 6. Effect of species concentration in suspended kaolinite on specific conductivity.

### Impact of secondary additives on kaolinite USS results

This phase consisted of batch tests in which the kaolinite soil was mixed with two main amendments: Na<sub>2</sub>SiO<sub>3</sub> and H<sub>3</sub>PO<sub>4</sub>, each in solutions of various concentrations. Also CaCl<sub>2</sub> and Al<sub>2</sub>(SO<sub>4</sub>)<sub>3</sub> were used as a secondary additive to find their effects enhanced USS of baseline soil. While Na<sub>2</sub>SiO<sub>3</sub> was selected as the primary amendment, H<sub>3</sub>PO<sub>4</sub> was also tested to provide background values for assessment and analyses of the results, particularly the effect of soil alkalization and acidification versus the effect of introducing silicate and phosphate ions in the base soil. The data provided strongly support that CaCl<sub>2</sub> can enhance EO injection and in addition to the EO effects, the increase of cation in the soil due to the injection of CaCl<sub>2</sub> will result in an increase of electric conductivity,  $k_e$ . Also, it increases the hydration of cation, which causes more absorbed water, along with the cation, tending to migrate them towards the cathode. This means compared to the EO only, the EO injection using CaCl<sub>2</sub> will be certainly enhanced. As a result, the treated kaolinite soil specimens presented considerably increase in USS results for all stabilizers when compared with the USS of the natural kaolinite soil sample, which amounts to 12 to 15 kPa. The strength increased with an increase in the concentration of Na<sub>2</sub>SiO<sub>3</sub> (Figure 7). High strengths were achieved with a higher Na<sub>2</sub>SiO<sub>3</sub> stabilizer. However, using CaCl<sub>2</sub> and Al<sub>2</sub>(SO<sub>4</sub>)<sub>3</sub> optimized using main stabilizers as well as better conditions regarding injection as grout. As for the case of phosphoric acid (Figure 7b), the results indicate that, for increasing acid concentration, the changes are insignificant in the USS.

As mentioned, using CaCl<sub>2</sub> may improve the EO flow

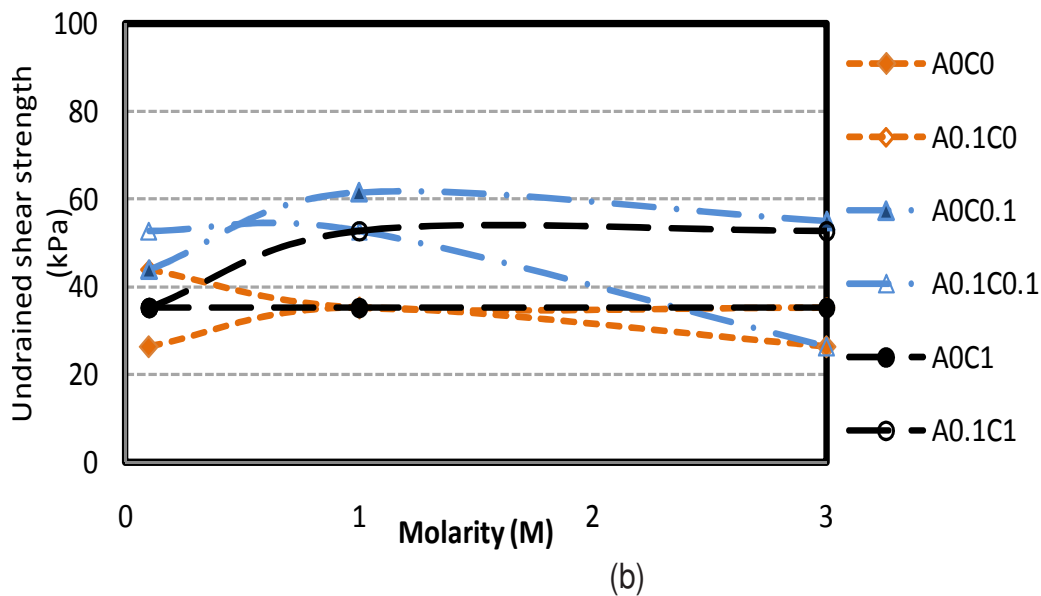
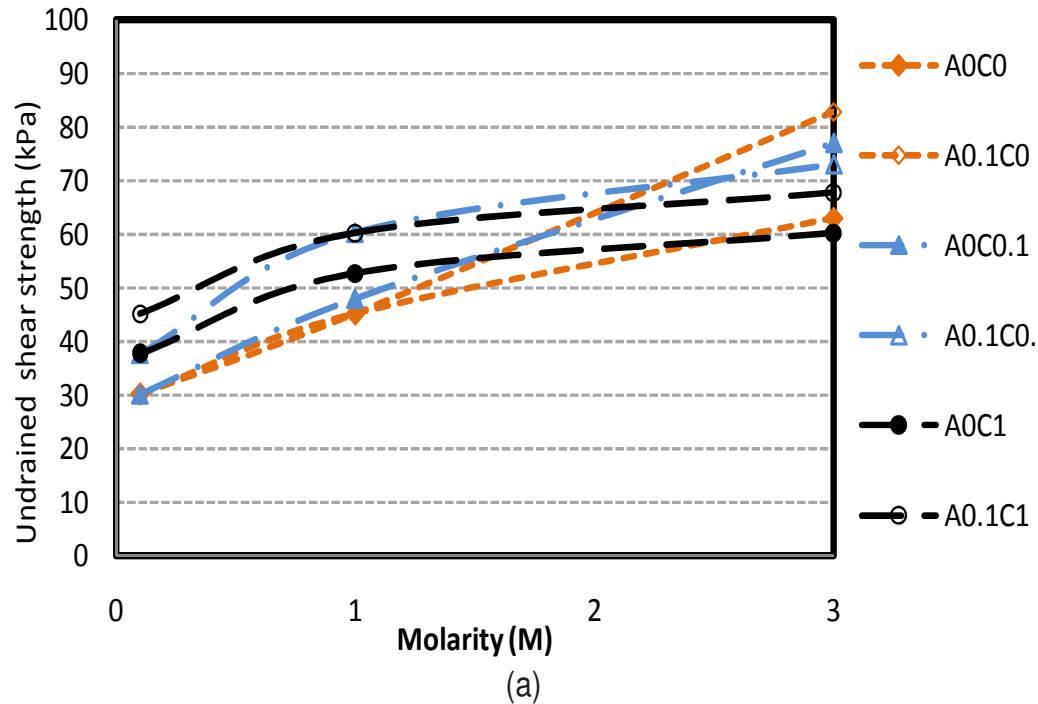
injection process, however it will reduce the USS properties of kaolinite soil (Figure 8). On the other hand, adding Al<sub>2</sub>(SO<sub>4</sub>)<sub>3</sub> in Na<sub>2</sub>SiO<sub>3</sub> treated soil increased the USS value significantly (Figure 9). As for 1 mol/L Na<sub>2</sub>SiO<sub>3</sub> and in the presence of 0.1 mol/L of Al<sub>2</sub>(SO<sub>4</sub>)<sub>3</sub>, the USS of kaolinite at 0, 0.1, and 3 mol/L CaCl<sub>2</sub> were 82.86, 73.0, and 67.80 kPa, respectively (Figure 9). Moreover, in the absence of Al<sub>2</sub>(SO<sub>4</sub>)<sub>3</sub>, the USS for 1 mol/L of Na<sub>2</sub>SiO<sub>3</sub> at 0, 0.1, and 1 mol/L CaCl<sub>2</sub> were 45.21, 48, and 52.74 kPa, respectively (Figure 9). However, having 0.1 mol/L of Al<sub>2</sub>(SO<sub>4</sub>)<sub>3</sub>, the USS for same molarities of Na<sub>2</sub>SiO<sub>3</sub> at 0, 0.1, and 1 mol/L CaCl<sub>2</sub> were 45.21, 60.27, and 60.27 kPa, respectively, which means using Al<sub>2</sub>(SO<sub>4</sub>)<sub>3</sub> increased USS results by 18 to 25% (Figure 9).

### Conclusions

This paper explained the effect of secondary additives on the EK stabilization phenomena. A series of zeta potential test were carried out as Phase I. It is focused more on the effect of different additives on EDL thickness of kaolinite colloidal surface. Compared to the measuring zeta potential which is done in water, adding even low molarities of the cations (0.001 mol/L) can cause a remarkable change of the zeta potential. Na<sub>2</sub>SiO<sub>3</sub> and H<sub>3</sub>PO<sub>4</sub> were selected as the main stabilizers. However, CaCl<sub>2</sub> and Al<sub>2</sub>(SO<sub>4</sub>)<sub>3</sub> were used as secondary additives. As for the second phase, a comprehensive series of UCS were carried out using 36 different binders. Based on the results of this study, the following conclusions may be drawn:

1) Compared to the EO flow only, the EO flow injection





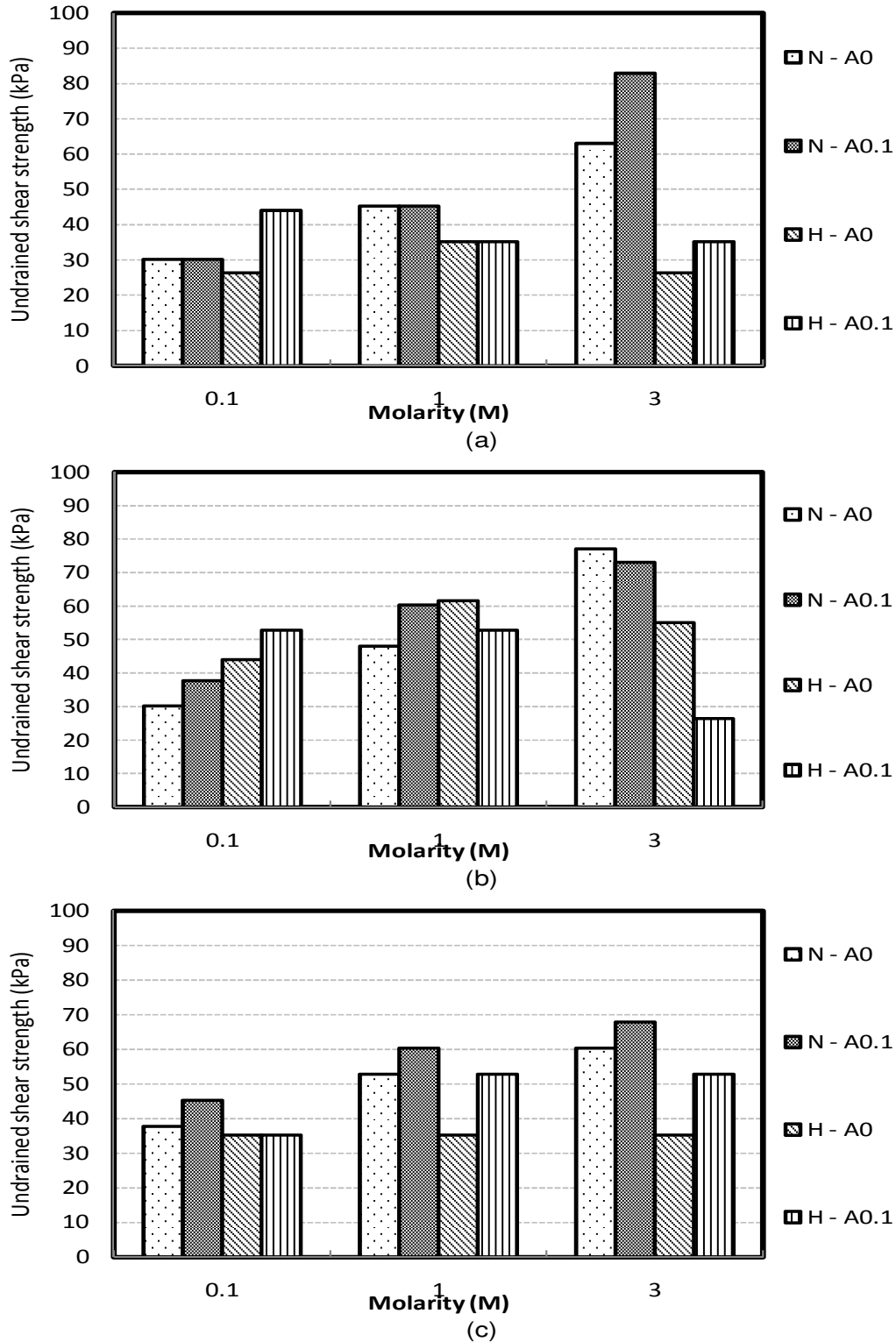
**Figure 7.** The 14 days USS results for treated kaolinite soil with; (a)  $\text{Na}_2\text{SiO}_3$  (b)  $\text{H}_3\text{PO}_4$ .

using  $\text{CaCl}_2$  will certainly improve the injection process. Using  $\text{CaCl}_2$  as a secondary additive remarkably enhanced EO flow injection due to increasing  $k_e$ , because it increases the hydration of cation. This can cause more absorbed water, along with the cation, tending to migrate them from the anode towards the cathode.

2)  $\text{Al}_2(\text{SO}_4)_3$  at 0, 0.1 mol/L as well as  $\text{CaCl}_2$  at 0, 0.1, and 1 mol/L were mixed as the secondary additive with  $\text{Na}_2\text{SiO}_3$  and  $\text{H}_3\text{PO}_4$  at 0.1, 1, and 3 mol/L as the main

stabilizer. Using  $\text{Al}_2(\text{SO}_4)_3$  enhanced USS even at low  $\text{Na}_2\text{SiO}_3$  molarities. This could be due to better interaction between  $\text{Na}_2\text{SiO}_3$  in the presence of  $\text{Al}_2(\text{SO}_4)_3$  in kaolinite and particle breakage.

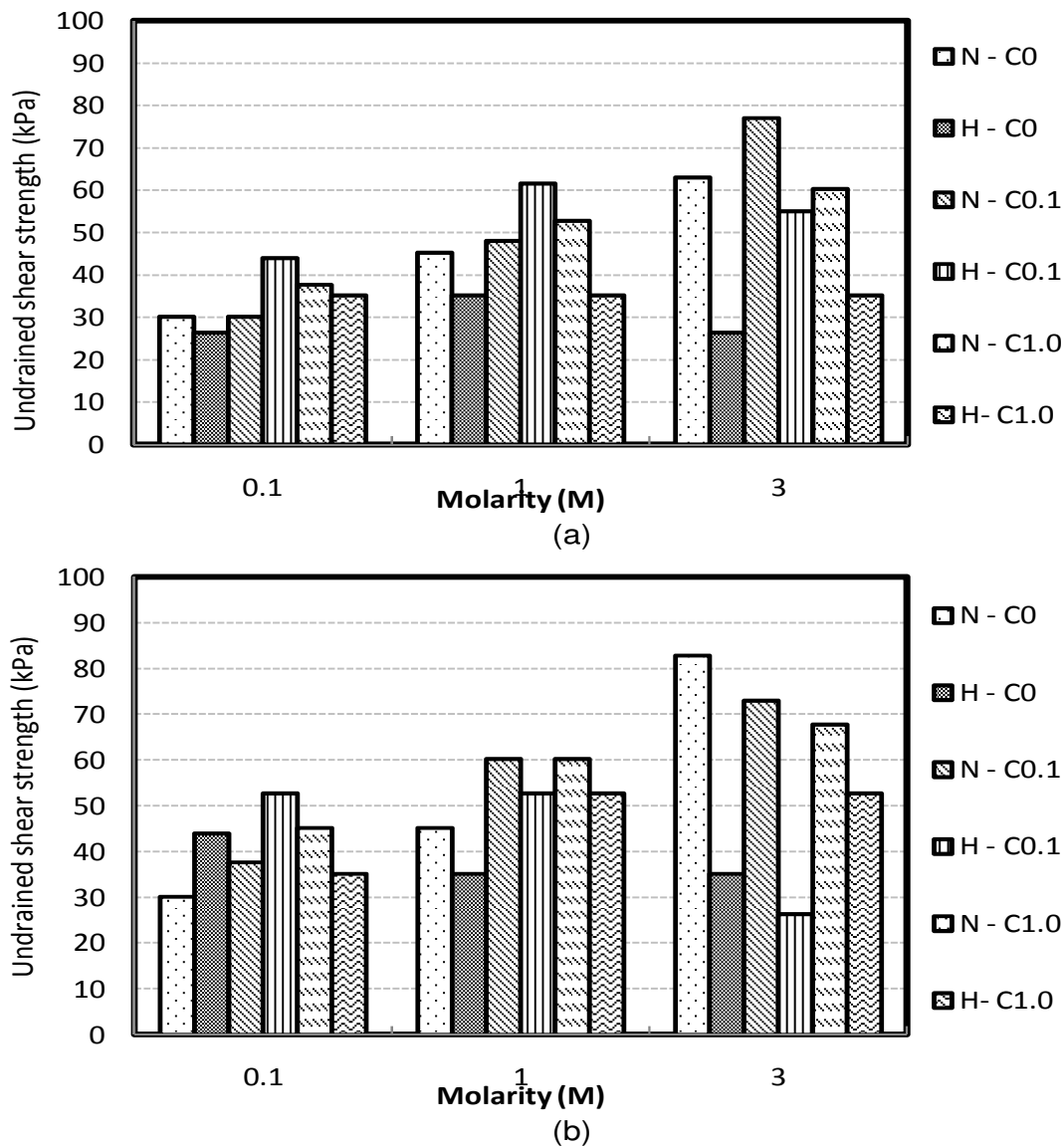
3) USS increased by up to 580% of the initial baseline soil's strength on addition of 3 mol/L of  $\text{Na}_2\text{SiO}_3$ . Although, lower concentrations of the main stabilizer led to lower USS results, adding  $\text{Al}_2(\text{SO}_4)_3$  showed better improvement in higher  $\text{Na}_2\text{SiO}_3$  molarities (Figure 7a).



**Figure 8.** Effect of electrolyte molarity on USS results of kaolinite soil; (a) Without CaCl<sub>2</sub>, (b) 0.1 mol/L CaCl<sub>2</sub>, and (c) 1.0 mol/L CaCl<sub>2</sub>.

4) In the presence of CaCl<sub>2</sub> at 0.1 mol/L and absence of Al<sub>2</sub>(SO<sub>4</sub>)<sub>3</sub>, the effect of using high Na<sub>2</sub>SiO<sub>3</sub> molarities as

for achieving high USS was reduced. However, the presence of CaCl<sub>2</sub> improved remarkably the USS of



**Figure 9.** Effect of electrolyte molarity on USS of kaolinite soil, (a) Without  $Al_2(SO_4)_3$ , and (b) 0.1 mol/L  $Al_2(SO_4)_3$ .

treated kaolinite with  $H_3PO_4$ . This effect in turn will contribute to an increase in permeability through fine soils. In contrast, negatively charged soil particles such as kaolinite, repel each other thus resulting in dispersion and decrease in soil permeability.

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