sciendo

CIVIL AND ENVIRONMENTAL ENGINEERING REPORTS

E-ISSN 2450-8594

CEER 2019; 29 (1): 128-146
DOI: 10.2478/ceer-2019-0010
Original Research Article

PLASTICITY AND SWELL-SHRINK BEHAVIOUR OF ELECTROKINETICALLY STABILIZED VIRGIN EXPANSIVE SOIL USING CALCIUM HYDROXIDE AND CALCIUM CHLORIDE SOLUTIONS AS CATIONIC FLUIDS

Jijo JAMES[1], Archana JAMES[2], Arun KUMAR[2], Elumalai GOMATHI[2] and Karunakaran Kamal PRASATH[2]
[1] SSN College of Engineering, Chennai, India.
[2] Jerusalem College of Engineering, Chennai, India

A b s t r a c t

This investigation focussed on the plasticity and swell-shrink behaviour of an expansive soil that was stabilized using electro kinetic stabilization (EKS) techniques with cationic fluids for enhancement of stabilization. 0.25 M solutions of calcium hydroxide and calcium chloride were used as cationic fluids. An electro kinetic (EK) cell of dimensions 500 mm x 150 mm x 160 mm with inert graphite electrodes of size 140 mm x 160 mm x 5 mm was adopted for the stabilization process, carried out at an applied voltage of 40 V over a period of 6 hours. After the duration of the test, stabilized soil sample was subjected to Atterberg limits and free swell tests to determine its plasticity and swell-shrink characteristics. The results of the investigation found that both fluids were capable of reducing the plasticity and swell-shrink behaviour of the soil with different levels of effectiveness.

Keywords: Electro kinetic Stabilization, Cationic fluid, Plasticity, Swell-shrink, Calcium chloride, Calcium hydroxide

[1] Corresponding author: SSN College of Engineering, Rajiv Gandhi Salai, Kalavakkam, Chennai – 603110, Tamil Nadu, India; jijoj@ssn.edu.in

1. INTRODUCTION

Expansive soils have long been known to be problematic due to their volume instability with variations in moisture content, resulting in disastrous effects for constructed infrastructure on top of them, especially lightly loaded structures. Such soils need to be engineered to make them volume stable to reduce their detrimental effects on structures. There are several methods available for stabilization of expansive soils, the most common being lime stabilization. However, in certain cases, the application of lime for treatment of such soft and expansive soils become difficult due to greater depth of the soil requiring treatment and poor hydraulic conductivity of the soils. Under such situations, Electro kinetic(s) (EK) method can be successfully adopted for stabilization of such soft and expansive soils. EK is an umbrella term used to denote the relationship between electrical potential and movement of water and charged particles [1]. The existence of such a phenomena was discovered due to the experiments conducted by a German scientist, Ferdinand Friedrich Reuss [2]. EK includes three major processes viz. electroosmosis, electrophoresis and electromigration [3]. Electroosmosis is the movement of pore fluid in a porous medium under applied voltage due to the development of hydraulic drag [4]. Electrophoresis is the movement of charged particles like clay minerals in a soil-water system. Electromigration is the migration of cations and anions towards the electrodes under the influence of the applied electric potential [5]. Apart from these, other allied phenomena include electrolysis, EK hardening and joule heating [1]. Since, the discovery of classic EK phenomena, other types like electroacoustics and diffusiophoresis have also been reported by researchers [2]. Electroosmosis is the most beneficial of all the EK processes as it has the capability to overcome limitations of extremely low flow in fine grained soils [1]. Early applications of EK was limited to dewatering and consolidation of soils as it is a well-known fact that water is directly related to the strength of the soil, its volume and movement of nutrients and contaminants. EK finds extensive applications in soil decontamination and remediation with extensive work done in the area. The first documented real life application of EK remediation for removal of salts from alkali soils was reported as early as in the 1930s from India [6]. Several researchers have worked on the use of EK in remediation of contaminated soils [5], [7]–[11]. Karim [11] states that the success of EK in soil remediation and decontamination validates its ability as a cost effective and viable in-situ remediation technique. However, the use of EK for soil improvement have been rare and limited to electroosmosis according to Abdullah and Al-Abadi [3]. Mosavat et al. [12] also conclude that most of the studies using EK have focussed on soil remediation and very few have focussed on the improvement of the mechanical and engineering properties of soils. Unlike, EK remediation, electro kinetic stabilization (EKS) of soil specifically deals with the improvement in physical and geotechnical properties of the soil, that enhances or improves the suitability of the soil as a geotechnical material. The improvement in the physical properties are attributed to the various electrochemical effects like electroosmosis, electromigration, electrolysis that take place during application of an electrical gradient [13]. Thus, it may be noted that the application of EK method for soil remediation also invariably results in changes to the physical properties of the soil resulting in soil improvement. EKS is a combination of electroosmosis and chemical grouting [13], wherein stabilizing agents are drawn into the soil by electroosmosis and electromigration and result in increased cementation. The major benefit of adopting EKS when compared to traditional mix in place treatment is that it enables remote treatment of the target soil layer without excavation [13]. There have been previous investigations where investigators have used stabilizing/enhancing agents for soil stabilization. The use of enhancing agents for improvement of soil during electroosmosis began in the 1990s [14]. Azhar et al. [13] state that these agents can be introduced from either anode or cathode of the EK cell, depending upon the ion to be fed. Ozkan et al. [15] used aluminium and phosphate ions for EKS of kaolinite. Alshawabkeh and Sheahan [16] investigated the stabilization of soft soil by electro-grouting using ionic amendments of phosphoric and nitric acids. Otsuki et al. [17] studied the feasibility of using anolyte and catholyte solutions in the electrochemical stabilization of a kaolinite soil. Abdullah and Al-abadi [3] investigated effect of Ca2+ and K+ ions as cationic stabilizing agents in EKS of a soil. Chien et al. [18] carried out laboratory investigations on the use of chemical solutions injection to improve soil by electroosmosis. Ranjitha and Blessing [19] investigated the effect of varying the concentration of cationic fluid and electrode combinations on the stabilization potential of EKS system. Moayedi et al. [20] attempted optimization of various stabilizing binders enhanced EKS to improve the physico-chemical properties of the soil. Traditionally, lime is used for stabilization of soft and expansive soils using mix in place techniques. In EKS, several investigators have adopted calcium chloride (CC) solution as cationic fluid [3], [14], [18]–[23]. In the available investigations on EKS in literature, a majority have concentrated on the shear strength of the stabilized soil [14], [16]–[18], [20], [23], whereas very few investigators have focussed on other properties like plasticity and swell [3], [15], [19], [21]. Thus, in this investigation an attempt was made to compare the effect of traditional lime in the form of a solution of calcium hydroxide (CH) with a solution of CC, when adopted as cationic fluids for stabilization of a high plastic expansive clay, on its plasticity and swell-shrink properties.

2. MATERIALS USED

A high plastic virgin expansive soil (VES), collected from Tiruvallur district of Tamil Nadu, India was adopted in the investigation. Laboratory grade CH and CC were adopted in the preparation of the cationic fluids for use in the investigation. Graphite electrodes supplied by M/s. Dhanalakshmi Industries, Chennai were used as anode and cathode in the investigation. The soil was characterized in the laboratory to determine its geotechnical properties and classified in accordance with the various codes of Bureau of Indian Standards (BIS). The properties of the soil determined from the laboratory characterization is tabulated in Table 1.

Table 1. Geotechnical Properties of the Soil

Property	Value
Specific Gravity [24]	2.67
Liquid Limit (%) [25]	66.2
Plastic Limit (%) [25]	26.3
Plasticity Index (%)	39.9
Shrinkage Limit (%) [26]	9.0
Free Swell Index (%) [27]	121.4
Maximum Dry Density (kN/m^3) [28]	15.4
Optimum Moisture Content (%) [28]	16.7
Soil Classification [29]	CH

3. EXPERIMENTAL SETUP

The EK cell adopted in the investigation was prepared using a glass case, graphite electrodes and an electric circuit board prepared to convert AC supply to DC supply. The experimental set up consisted of a glass chamber which is separated into three chambers viz. an anode chamber, a soil chamber and a cathode chamber, by the insertion of the electrodes in the guide frames provided for the installation of electrodes. The EK cell had a dimensions of 500 mm x 150 mm x 160 mm made with 5 mm thick glass panels. The length of the soil specimen in soil chamber was 150 mm. The anode and cathode compartments were each provided with a hole for flushing of the chambers and removal of dewatered liquid. The electrodes adopted in the investigation were inert graphite electrodes of dimensions 140 mm x 160 mm x 5 mm. 3 mm diameter holes were drilled into the graphite electrode at a vertical and horizontal spacing of 20 mm to allow the cationic fluid to be drawn into the soil and water to be drawn out of the soil from the cathode during the EK process. Electric circuitry was adopted to step down the AC voltage of 220 V coming from the AC mains to a constant DC voltage of 40 V, by means of a step-down transformer, a bridge rectifier and a shunt capacitance filter. Figure 1 shows the experimental set up adopted in the investigation.

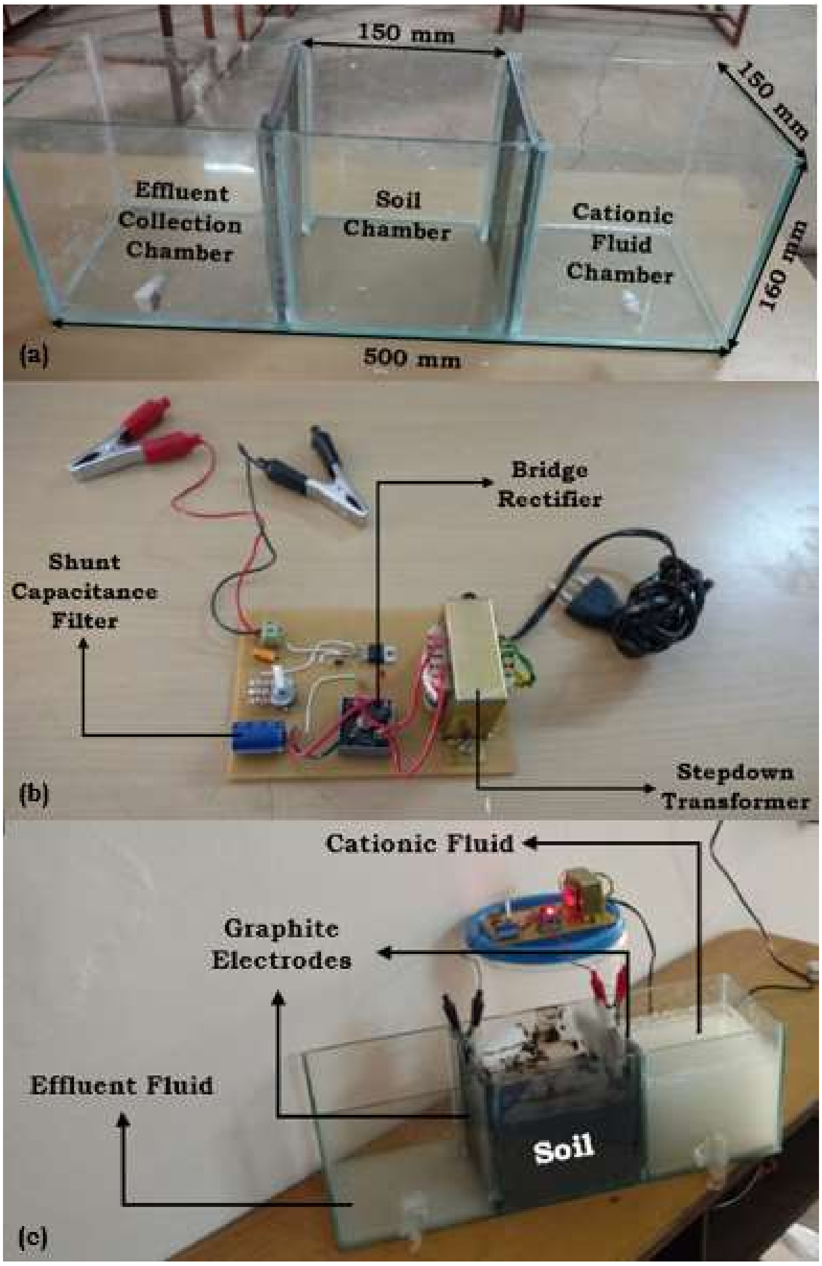

Fig. 1. A view of (a) EK Cell (b) Circuitry (c) Experimental Set Up

4. METHODS

The soil sample passing through BIS 425-micron sieve was adopted in the investigation. 2 kg of sieved soil sample at a water content of 60% was prepared for each trial by careful manual mixture of soil and water such that a smooth soil paste was obtained without any lumps. The electrodes were inserted into the slots provided and filter paper was placed on the interiors of the graphite electrodes in the soil chamber. This was done to prevent the movement of soil particles across the holes drilled in the electrodes and ensure clog free movement of fluid. The soil paste was then placed in layers for uniform deposition of soil. The strength of both the cationic fluids was fixed as 0.25 M and 3.5 litres of each fluid was prepared for every trial and poured into the anode chamber for conducting the EKS experiment. For the purpose of simplicity and recognition, CH fluid stabilized soil was designated as EKSCH and CC fluid stabilized soil was designated as EKSCC. The electrodes were then connected to the circuit by means of clamps and a voltage of 40 V was applied to the specimen for a period of 6 hours. At the end of the six hours, the power supply was disconnected and the entire soil specimen was removed from the soil chamber and thoroughly mixed manually to get an even mix. The mixed soil was then air dried for a period of 24 hours followed by oven drying for another 24 hours at 110oC. This soil was then pulverized and sieved through BIS 425-micron sieve and then was used to determine the plasticity and swell-shrink of the soil by conducting Atterberg limits, and free swell index in accordance to codes of BIS. Three trials were conducted for each test and the average was reported as the result of a particular test.

5. RESULTS AND DISCUSSION

The investigation involved the determination of the effect of cationic fluid enhanced EKS on the plasticity and swell-shrink of an expansive soil. The effect of EKS on the plasticity was evaluated by conducting the liquid limit and plastic limit test in accordance with BIS code [25] and determining the plasticity from the result of the tests. The effect on swell-shrink behaviour was determined by conducting the free swell index test [27] and the shrinkage limit test [26] both in accordance to BIS codes. Similar combination of free swell and shrinkage limit has been adopted

5.1. Effect on Plasticity

Figure 2. shows the variation of the liquid limit of the VES after EKS using CH and CC cationic fluids.

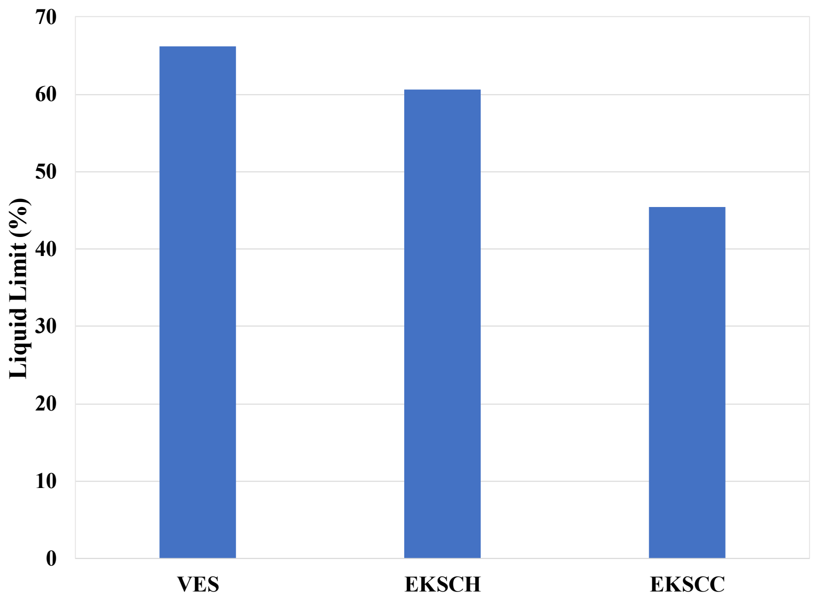

Fig 2. Liquid Limits of VES before and after EKSCH and EKSCC

It can be seen that the use of both cationic fluids has resulted in a reduction in liquid limit of the VES. However, it can be seen that CC stabilized VES resulted in a better reduction in liquid limit when compared to CH stabilized VES. The liquid limit reduced from 66.2% for the VES to 60.6% for EKSCH, whereas it reduced to 45.4% for EKSCC. Thus, it is clear from the results that EKSCC is better in reducing the liquid limit when compared to EKSCH. CH is able to reduce liquid limit by just around 6% whereas CC is able to reduce the liquid limit by more than 20%. Thus, CH is able to achieve a percentage reduction (with respect to original liquid limit) of just 8.5% whereas CC is able to achieve close to 31.5%. It is well known that the reduction in liquid limit due to the addition of lime to an expansive soil is due to short term reactions taking place between the soil and lime including cation exchange and flocculation agglomeration of clay [30]. However, in the present case, the effect of similar concentrations of CH and CC produced different results with CC fluid resulting in a significantly reduced liquid limit in the case of EKSCC. The inherent reactions in the case of CC stabilization is also same with cation exchange taking place. But, the enhanced effect of CC can be attributed to its ability to readily dissolve in water to produce a charged supernatant liquid compared to lime which helps in ready cation exchange reactions [31]. Figure 3 shows the effect of the cationic fluids on the plastic limit of VES.

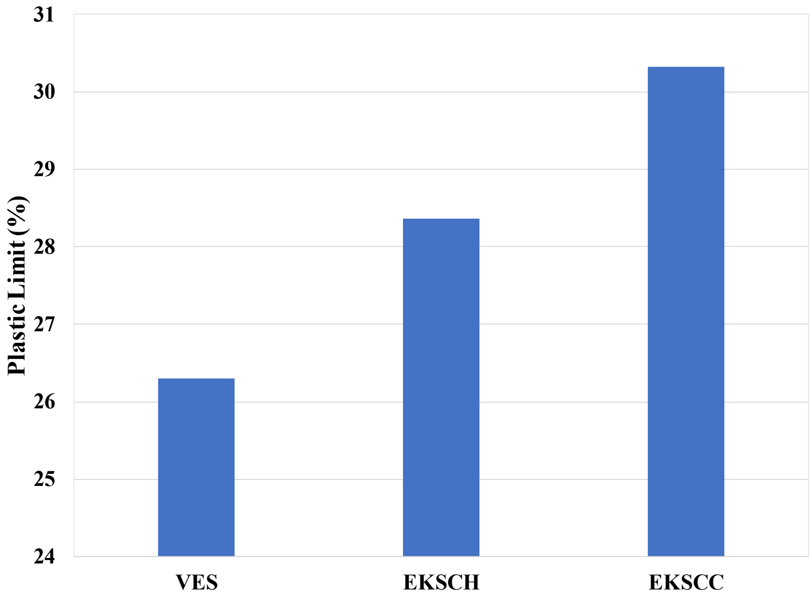

Fig 3. Plastic Limits of VES before and after EKSCH and EKSCC

It can be seen that EKS of VES results in an increase in plastic limits for both CH and CC fluids. However, just like the trend in the case of liquid limit, in the case of plastic limit as well, the increase in plastic limit due to CC fluid is higher than that of CH fluid. The plastic limit increased from 26.3% to 28.4% for CH fluid whereas it increased to 30.3% for CC fluid. Thus, the increase in plastic limit achieved by EKSCC is almost double that of EKSCH. In terms of percentage increase in plastic limit (with respect to original), EKSCH resulted in a 7.9% increase in plastic limit whereas EKSCC resulted in a 15.3% increase in plastic limit of the stabilized soil. Figure 4 shows the effect of CH and CC fluids on plasticity of EKS of VES. It can be seen that the combined effect of reduction in liquid limit and increase in plastic limit has resulted in a reduction in plasticity of the stabilized soil for both CH and CC stabilized soil. Azhar et al. [21] and Abdullah and Abadi [3] reported a reduction in plasticity index of the soil due to EKS using enhancement fluids like calcium chloride whereas Ozkan et al. [15] reported a contrasting trend of increase in Atterberg limits due to EKS when using aluminium and phosphate ions injection.

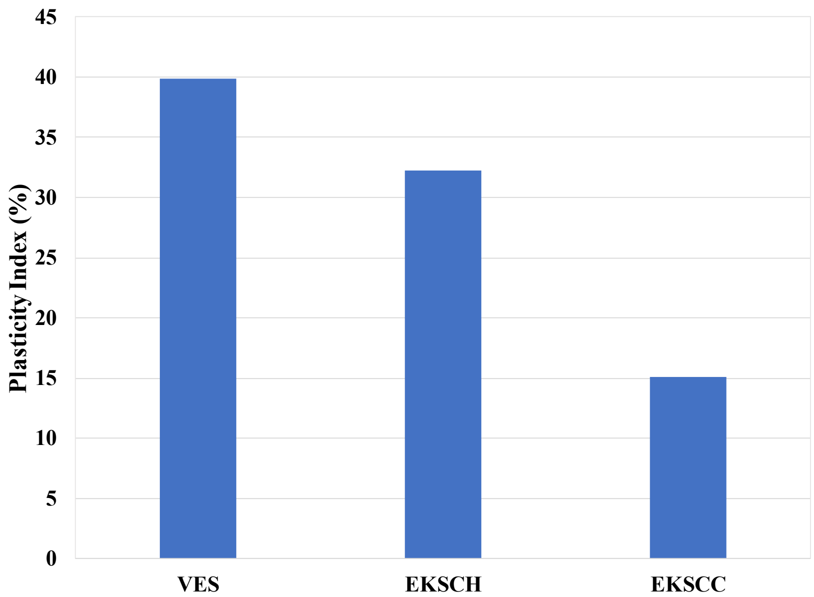

Fig 4. Plasticity Index of VES before and after EKSCH and EKSCC

The plasticity index of EKSCH reduced to 32.2% from the initial value of 39.9% for VES, whereas it reduced to 15.1% for EKSCC, a drastic reduction in plasticity index, predominantly due to the reduction in liquid limit. In terms of percentage reduction (with respect to original plasticity index), the reductions were 19.2% and a huge 62.2% for the former and latter respectively. The reduction in plasticity of the VES due to CH and CC fluids are predominantly due to cation exchange [30], [32], reduction in thickness of diffused double layer with increase in electrolyte concentration [33], increase in viscosity of pore fluid due to adsorption of calcium ions [33]. Injection of CC into the soil results in an enhanced electrical conductivity and hydration of cations, which cause more adsorbed water along with cations to move towards cathode resulting in a greater improvement of the soil [18], [20]. This coupled with ion exchange and flocculation may be the reason for the enhanced effectiveness of the CC fluid in EKS.

Figure 5 shows the effect of EKSCH and EKSCC on the classification of the VES. It is clear that the EKS results in a change in classification of the VES. Due to the enhanced effect of CC fluid over CH fluid, the former results in significant change in the classification status of the VES when compared to the latter. The classification of VES does not change due to EKSCH with the both being classified as clay of high plasticity, EKSCH is able to move the position of the plot point on the plasticity chart. On the other hand, the significant reduction in the liquid limit and plasticity index of the CC stabilized soil has resulted in

EKSCC classification moving from clay of high plasticity zone to silt of intermediate plasticity zone, which is a major change in classification of the VES. Thus, according to BIS classification, EKSCC has resulted in a significant change in the characteristics of the soil to be classified as silt of intermediate plasticity.

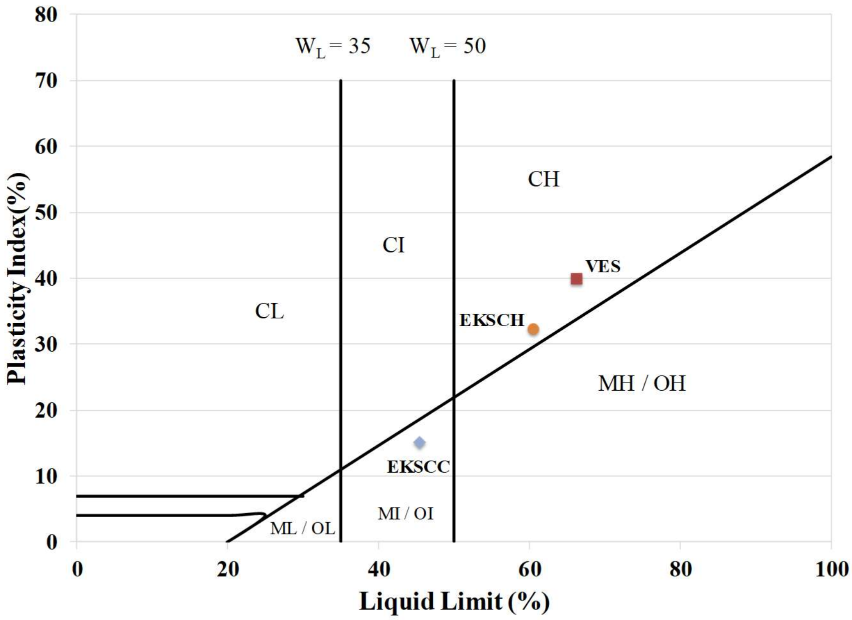

Fig 5. Classification of VES before and after EKSCH and EKSCC

5.2. Effect on Swell-shrink Behaviour

Figure 6 shows the effect of EKS on the free swell of VES using CH and CC fluids. It is clear from the graph, that both EKSCH and EKSCC are capable of reducing the free swell of the VES. However, in contrast to the influence on plasticity, the influence on swell due to EKSCH and EKSCC is completely opposite. EKSCH is capable of a better swell control when compared to EKSCC. The swell of VES reduces from 121.4% to 100% when EKSCC is adopted. However, in the case of EKSCH, the same swell reduces further to 73.4%. The quantum of reduction in swell because of CH is more than double that of CC fluid.

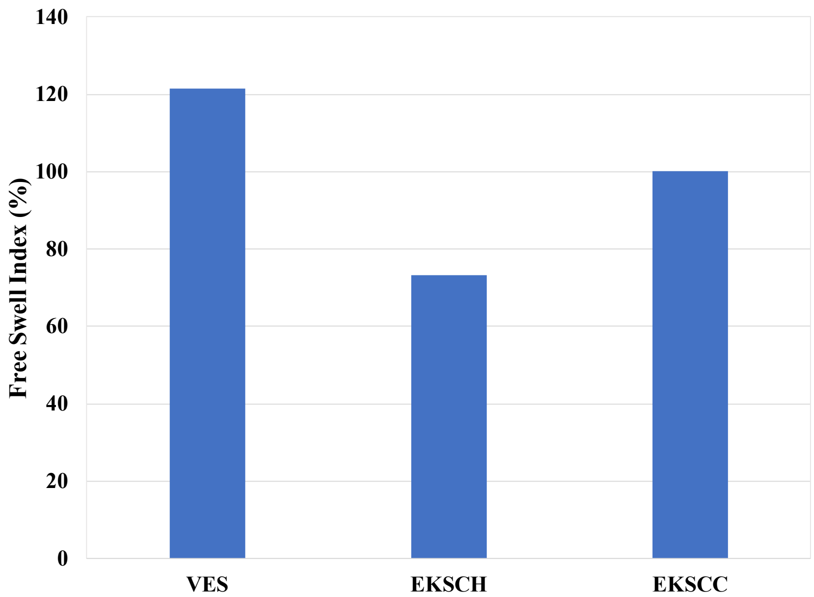

Fig 6. Free Swell of VES before and after EKSCH and EKSCC

In terms of percentage reduction in swell (compared to original free swell), CH reduces the swell by 39.6% whereas CC is capable of only a 17.6% reduction in swell. Reduction in swell indicates an improvement in soil properties due to EKS. Thus, it can be concluded the EKSCH and EKSCC are effective in swell control of an expansive soil. But the swell control trends were opposite to that of reduction in plasticity with CH resulting in a greater reduction in swell compared to CC. This was in contrast to the result reported by Abdullah and Abadi [3] who reported CC to be more effective in swell control when compared to CH fluid. Figure 7 shows the effect of EKSCH and EKSCC on the shrinkage limit of VES. The trends in improvement of shrinkage limit were also similar to that of free swell index wherein EKS resulted in an increase in the shrinkage limit, with EKSCH performing better when compared to EKSCC. The shrinkage limit increased from 9% for VES to 12.8% for EKSCC and 16% for EKSCH. It can be seen that the increase in shrinkage limit for EKSCH is close to double that of the increase for EKSCC. In terms of percentage increase (with respect to original shrinkage limit), the EKSCC gives a 42.4% improvement in shrinkage limit whereas EKSCH is capable of a 77.5% improvement in shrinkage limit. Increase in shrinkage limit is a clear indication of the improvement in the shrinkage behaviour of the soil. James and Pandian [34] state that increase in shrinkage limit results in reduction in the range over which volume change can occur due to loss of moisture, thereby reducing the volume change zone.

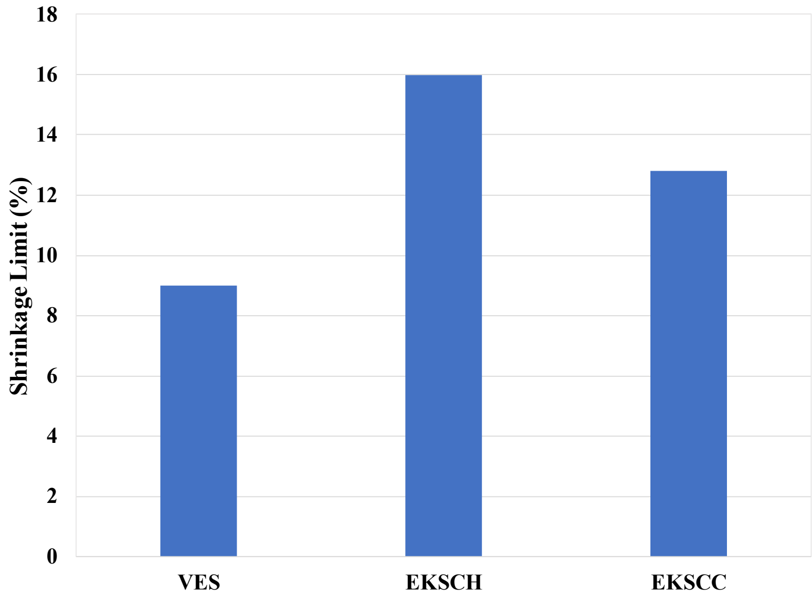

Fig 7. Shrinkage Limit of VES before and after EKSCH and EKSCC

5.3. A Comparative Evaluation

To study the extent of improvement achieved due to the use of cationic fluids in EKS for the present soil, an attempt was made to compare the effect of improvement achieved with results of earlier investigations. Since very few investigations have focussed on the plasticity and swell-shrink of the soil, the number of investigations available for comparison were limited. In the available investigations, only those investigations were considered which used either CH or CC as cationic fluid for EKS. Specifically, three investigations done by Abdullah and Abadi [3], Azhar et al. [21] and Ranjitha and Blessing [19] were considered for the comparison as all three investigations adopted CC fluid as one of their/only cationic fluid for EKS. According to Page and Page [35], electrolyte composition, pH, electrical conductivity, field strength, water content, soil chemistry, soil structure, nature and arrangement of electrodes are some important factors influencing EK. The three investigations adopted different soil, applied voltage, electrolyte concentration and duration of testing. All three investigations had reported the electrolyte concentration adopted for the cationic fluid, the applied voltage or field strength and the duration of the EKS. In order to bring all the investigations to a more level field of comparison, the reductions achieved for plasticity and swell were likened. The shrink parameter could not be compared as none of the selected investigations had focussed on the shrinkage behaviour of the soil. The reduction ratio was calculated as the ratio of the reduction in plasticity or swell to the original value expressed in %. This reduction ratio was adjusted for the applied voltage and the electrolyte concentration adopted in the present investigation. The data was not normalized for duration of testing due to non-linear relationship between the duration and stabilization or improvement achieved and extreme variations in the durations adopted by the various studies considered. Since, the present investigation determined the average values of plasticity and swell, the data reported by Abdullah and Abadi [3] as well as Azhar et al. [21] for different locations within the soil were combined to obtain a single average data for the purpose of comparison. Figure 8 shows the comparison of the normalised percentage reduction achieved in plasticity of the soil after EKS in various studies considered.

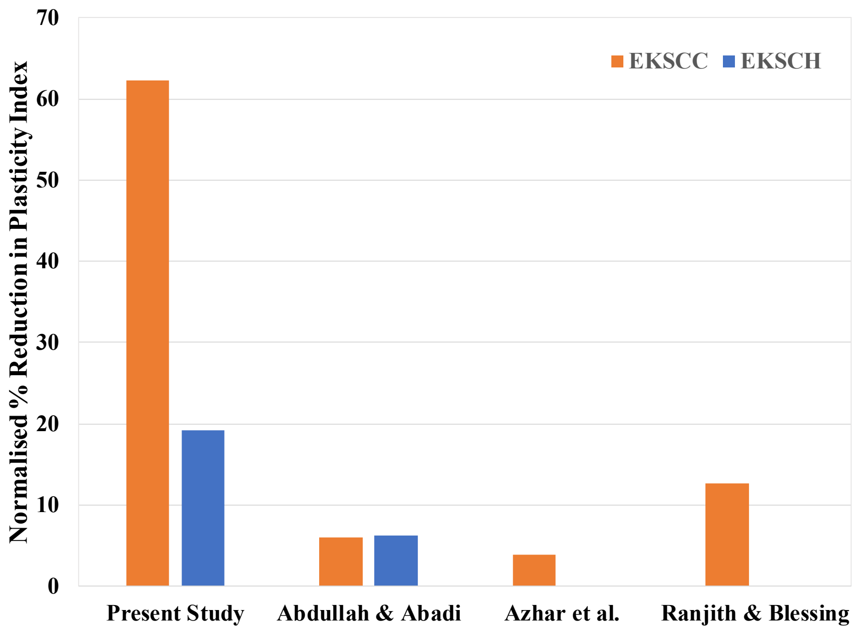

Fig 8. Comparison of Plasticity Reduction of the Present Study with Previous Studies

Azhar et al. [21] and Ranjith and Blessing [19] had adopted only CC fluid in their investigations. It can be clearly seen that CC fluid adopted in the present study gave the maximum reduction in plasticity compared to all the four studies. The reduction in plasticity achieved was 62.2% followed by 12.6% in the study conducted by Ranjith and Blessing [19]. The least reduction in plasticity was found to be in the case of Azhar et al. [21] at 3.9%. The other major difference noticed is the huge difference in improvement achieved between CH and CC fluid compared to the work done by Abdullah and Abadi [3]. They reported more or less same effect on plasticity due to CH as well as CC fluids with the plasticity reductions being 6.25% and 6.04% respectively. This may be due to the difference in soil composition and chemistry.

Figure 9 shows the comparison of the normalised percentage reduction in free swell achieved in the various studies considered. Azhar et al. [21] had not focussed on the swell of the soil in his investigation. It is clear that the maximum reduction in swell in achieved by CC fluid in the work done by Ranjith and Blessing [19]. The reduction in free swell achieved was 65.7% when compared to 17.6% in the present study for CC fluid. However, CH fluid was able to achieve a reduction of 39.6% for the soil under investigation. In the case of the work done by Abdullah and Abadi [3], it is seen that just like in the case of plasticity, in the case of free swell as well there was no big difference in the performance of CH and CC fluids with the swell reduction being 25.2% and 26.5% for CH and CC fluids respectively. This was in contrast to the effect of the two fluids on the present soil wherein both fluids gave significantly different results for both plasticity and swell.

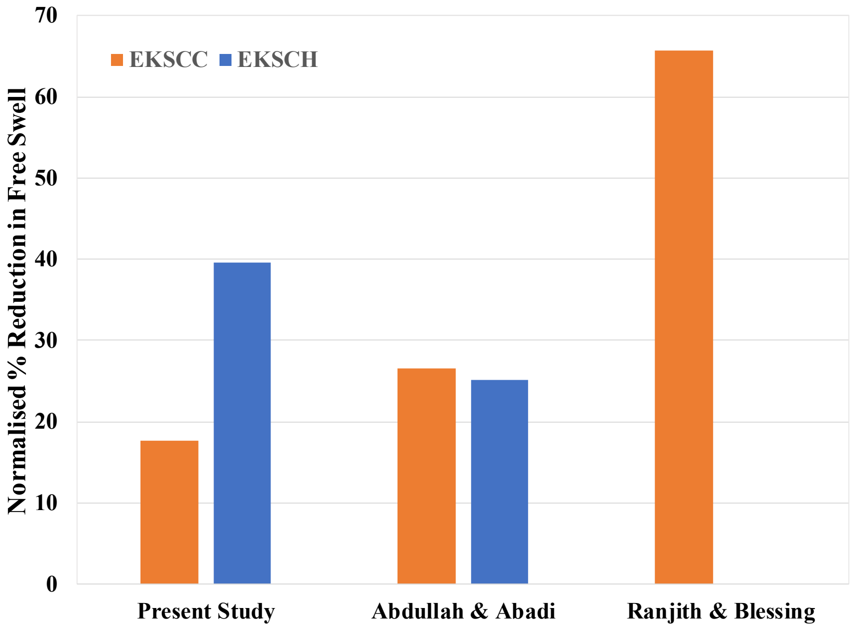

Fig 9. Comparison of Free Swell Reduction of the Present Study with Previous Studies

On closer observation, it may be noted that in the work done by Abdullah and Abadi [3], CH fluid gave a marginally better reduction in plasticity whereas CC fluid performed better in the case of swell control. A similar trend was observed in the present study as well but with the difference that CC performed well in plasticity reduction while CH performed better in swell control. This may be again due to the difference in soil composition and chemistry. Thus, it is possible to state that effectiveness of improvement of soils will vary with the cationic fluid despite the cation in question being the same. Secondly, it is also possible to state, though with lesser amount of certainty, that different cationic fluids have varying effects on different properties of the soil like plasticity and swell-shrink, subject to soil composition and chemistry. This needs to be verified with more detailed investigations using different cationic fluids focussed on different sets of properties of various soils.

6. CONCLUSIONS

The investigation focussed on the effect of using two different cationic fluids namely CH and CC fluids on the plasticity and swell-shrink behaviour of an electrokinetically stabilized expansive soil. Based on the review of earlier studies and the results of the present investigation, the following points may be concluded:

(i) Very few investigations have been carried out in EKS of soils using cationic fluids despite EKS providing the advantage of remote stabilization of soils. In the few investigations carried out, CC fluid has been, by far, the most common cationic fluid adopted for EKS. Majority of the investigations focus only on the improvement of shear strength whereas little focus has been put upon other properties like plasticity and swell-shrink behaviour.

(ii) EKS of the VES with CH and CC fluids resulted in a reduction in plasticity of the soil from 39.9% to 32.2% and 15.1% amounting to a percentage reduction of 19.2% and 62.2% respectively, with respect to the plasticity of VES. It can be concluded that CC fluid is more effective in reducing the plasticity of the soil when compared to CH fluid. Due to the effectiveness of CC fluid in plasticity reduction, it is capable of also changing the classification of the expansive soil from high plastic clay to silt of intermediate plasticity, which CH fluid is unable to achieve.

(iii) EKS of VES with CH and CC fluids reduced the swell-shrink behaviour of the expansive soil by reducing the free swell and increasing the shrinkage limit. The reduction in free swell was of the order of 39.6% and 17.6% respectively for CH and CC fluids whereas in shrinkage limit was 77.5% and 42.4% respectively, all with respect to the original values of VES. Based on the swell-shrink results, it can be concluded that CH fluid is better capable of stabilizing the swell-shrink behaviour when compared to CC fluid for the soil under investigation, which contrasts the stabilized plasticity behaviour of the same with CH and CC fluids.

(iv) Based on the comparative evaluation of the present study with similar previous studies, it can be stated that the effectiveness of the improvement achieved using cationic fluids depends upon the fluid used despite the cation being the same. It can also be stated that the different fluids can have varying degree of effects on the diverse properties of a soil, though more detailed investigations with different fluids and soils are required to come to concrete conclusions to this effect.

In short, it can be stated that EKS using cationic fluids can be used effectively for target modification of different properties of the soil by carefully selecting the fluid for the purpose of modification expected.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest in the publication of this article.

REFERENCES

[1] Jones, CJFP, Lamont-Black, J and Glendinning S 2011. Electrokinetic geosynthetics in hydraulic applications. Geotext. Geomembranes 29, 381–390.
[2] Wall, S 2010. The history of electrokinetic phenomena. Curr. Opin. Colloid Interface Sci. 15, 119–124.
[3] Abdullah, WS and Al-Abadi, AM 2010. Cationic–electrokinetic improvement of an expansive soil. Appl. Clay Sci. 47, 343–350.
[4] Acar, BYB, Li, H and Gale, RJ 1992. Phenol removal from kaolinite by electrokinetics. J. Geotech. Eng. 118, 1837–1852.
[5] Cameselle, C and Gouveia, S 2013. Advances in Electrokinetic Remediation for the Removal of Organic Contaminants in Soils. In: Rashed, MN (Ed.) Organic Pollutants - Monitoring, Risk and Treatment. InTech Open, 209–229.
[6] Jiang, H, Wang, B, Inyang, HI, Liu, J, Gu, K and Shi, B 2013. Role of expansive soil and topography on slope failure and its countermeasures, Yun County, China. Eng. Geol. 152, 155–161.
[7] Yuan, C, Hung, C-H and Chen, K-C 2009. Electrokinetic remediation of arsenate spiked soil assisted by CNT-Co barrier-the effect of barrier position and processing fluid. J. Hazard. Mater. 171, 563–70.
[8] Ouhadi, VR, Yong, RN, Shariatmadari, N, Saeidijam, S, a Goodarzi, R and

Safari-Zanjani, M 2010. Impact of carbonate on the efficiency of heavy metal removal from kaolinite soil by the electrokinetic soil remediation method. J. Hazard. Mater. 173, 87–94.

[9] Cameselle, C, a Chirakkara, R and Reddy, KR 2013. Electrokinetic-enhanced phytoremediation of soils: status and opportunities. Chemosphere 93, 626–36.

[10] Ren, L, Lu, H, He, L and Zhang, Y 2014. Enhanced electrokinetic technologies with oxidization–reduction for organically-contaminated soil remediation. Chem. Eng. J. 247, 111–124.

[11] Karim, MA 2014. Electrokinetics and soil decontamination: concepts and overview. J. Electrochem. Sci. Eng. 4, 297–313.

[12] Mosavat, N, Oh, E and Chai, G 2012. A Review of Electrokinetic Treatment Technique for Improving the Engineering Characteristics of Low Permeable Problematic Soils. Int. J. Geomate 2, 266–272.

[13] Azhar, ATS, Azim, MAM, Syakeera, NN, Jefferson, IF and Rogers, CDF 2017. Application of Electrokinetic Stabilisation (EKS) Method for Soft Soil: A Review. IOP Conf. Ser. Mater. Sci. Eng. 226.

[14] Ou, C, Chien, S and Wang, Y 2009. On the enhancement of electroosmotic soil improvement by the injection of saline solutions. Appl. Clay Sci. 44, 130–136.

[15] Ozkan, S, Gale, RJ and Seals, RK 1999. Electrokinetic stabilization of kaolinite by injection of Al and PO43- ions. Gr. Improv. 3, 135–144.

[16] Alshawabkeh, AN and Sheahan, TC 2003. Soft soil stabilisation by ionic injection under electric fields. Gr. Improv. 7, 177–185.

[17] Otsuki, N, Yodsudjai, W and Nishida, T 2007. Feasibility study on soil improvement using electrochemical technique. Constr. Build. Mater. 21, 1046–1051.

[18] Chien, S, Ou, C and Wang, Y 2011. Soil improvement using electroosmosis with the injection of chemical solutions: laboratory tests. J. Chinese Inst. Eng. 34, 863–875.

[19] Ranjitha, K and Blessing, BVM 2017. Soil Stabilization by Electrokinetic Method. Int. J. Sci. Res. 6, 1316–1320.

[20] Moayedi, H, Asad, A, Moayedi, F, Huat, BBK and Chea, LW 2011. Optimizing stabilizers enhanced electrokinetic environment to improve physicochemical properties of highly organic soil. Int. J. Electrochem. Sci. 6, 1277–1293.

[21] Azhar, ATS. et al. 2018. The Physical Behavior of Stabilised Soft Clay by Electrokinetic Stabilisation Technology. J. Phys. Conf. Ser. 995, 1–10.

[22] Mohamedelhassan, E and Shang, JQ 2003. Electrokinetics-generated pore fluid and ionic transport in an offshore calcareous soil. Can. Geotech. J.

40,1185–1199.

[23] Chien, S, Ou, C and Lee, Y 2010. A novel electroosmotic chemical treatment technique for soil improvement. Appl. Clay Sci. 50, 481–492.

[24] BIS, IS 2720 Methods of Test for Soils Part 3: Determination of Specific Gravity/Section 1 Fine Grained Soils. India 1980, 1–8.

[25] BIS, IS 2720 Methods of Test for Soils: Part 5 Determination of Liquid and Plastic Limit. India 1985, 1–16.

[26] BIS, IS 2720 Methods of Test for Soils: Part 6 Determination of Shrinkage Factors. India 1972, 1–12.

[27] BIS, IS 2720 Methods of Test for Soils: Part 40 Determination of Free Swell Index of Soils. India 1977, 1–5.

[28] BIS, IS 2720 Methods of Test for Soils: Part 7 Determination of Water Content-Dry Density Relation Using Light Compaction. India 1980, 1–9.

[29] BIS, IS 1498 Classification and Identification of Soils for General Engineering Purposes. India 1970, 4–24.

[30] Little, DN 1995. Handbook for Stabilization of Pavement Subgrades and Base Courses with Lime. Austin: Texas.

[31] Prasad, ASSV, Prasad, DSV and Babu, RD 2015. Efficiency of Calcium Chloride and Vitrified Tiles Sludge on the Strength Characteristics of Expansive Soil. Int. J. Adv. Res. Educ. Technol. 2, 202–205.

[32] Bhuvaneswari, S, Thyagaraj, T, Robinson, RG and Gandhi, SR 2010. Alternative Technique to Induce Faster Lime Stabilization Reaction in Deeper Expansive Strata. Proceedings of Indian Geotechnical Conference GEOtrendz, Mumbai, India, December, 16–18, 609–612.

[33] Sivapullaiah, PV and Jha, AK 2014. Gypsum Induced Strength Behaviour of Fly Ash-Lime Stabilized Expansive Soil. Geotech. Geol. Eng. 32, 1261–1273.

[34] James, J and Pandian, PK 2016. Plasticity, Swell-Shrink and Microstructure of Phosphogypsum Admixed Lime Stabilized Expansive Soil. Adv. Civ. Eng. Article ID 9798456, 1–10.

[35] Page, MM and Page, CL 2002. Electroremediation of Contaminated Soils. J. Environ. Eng.128, 208–219.

PLASTYCZNOŚĆ I KURCZENIE SIĘ GLEBY W STABILIZACJI ELEKTROKINETYCZNEJ Z WYKORZYSTANIEM WODOROTLENKU WAPNIA I CHLORKU WAPNIA JAKO PŁYNÓW KATIONOWYCH

Streszczenie

W badaniach skupiono się na plastyczności i kurczeniu się gleby, która została ustabilizowana za pomocą technik stabilizacji elektrokinetycznej (EKS) z płynami kationowymi. Jako płyny kationowe stosowano 0,25 M roztwory wodorotlenku wapnia i chlorku wapnia. Do procesu stabilizacji przyjęto ogniwo elektrokinetyczne (EK) o wymiarach 500 mm x 150 mm x 160 mm z obojętnymi elektrodami grafitowymi o wymiarach 140 mm x 160 mm x 5 mm, przy zastosowaniu napięcia 40 V przez okres 6 godzin. Po zakończeniu testu stabilizowaną próbkę gleby poddano testom Atterberga i badaniom swobodnego spęcznienia w celu określenia jego plastyczności i charakterystyki kurczenia się. Wyniki badania wykazały, że oba płyny były w stanie zmniejszyć plastyczność i kurczenie się gleby przy różnych poziomach skuteczności.

Słowa kluczowe: stabilizacja elektrokinetyczna, płyn kationowy, plastyczność, kurczliwość pęcznienia, chlorek wapnia, wodorotlenek wapnia

Editor received the manuscript: 04.02.2019