2021-09-26

Development of a new electro-osmotic consolidation apparatus

Yenni Mariana Ramírez-Mazo
Universidad de Antioquia, mariana.ramirez@udea.edu.co

Juan Pablo Osorio
Technological University Dublin, juan.osorio@tudublin.ie

Sergio Agudelo
Universidad de Antioquia, sergio.agudelo@udea.edu.co

Recommended Citation

Ramírez-Mazo, Yenni Mariana; Osorio, Juan Pablo & Agudelo, Sergio. (2021). Development of a new electro-osmotic consolidation apparatus. In: 6th International Conference on Geotechnical and Geophysical Site Characterization. 26 – 29 September 2021. Budapest, Hungary. Hungarian Geotechnical Society. DOI: 10.21427/BJJW-3S84

Funder: Universidad de Antioquia

Development of a new electro-osmotic consolidation apparatus

Yenni Mariana Ramírez-Mazo
GeoResearch International – GeoR, Escuela Ambiental, Facultad de Ingeniería, Universidad de Antioquia UdeA, Calle 70 No. 52-21, Medellín, Colombia, mariana.ramirez@udea.edu.co.

Juan Pablo Osorio
School of Civil and Structural Engineering, Technological University Dublin,
City Campus, Bolton Street, Dublin 1, D01 K822, Ireland, juan.osorio@tudublin.ie

Sergio Agudelo
Grupo Energía Alternativa - GEA, Departamento de Ingeniería Mecánica, Facultad de Ingeniería,
Universidad de Antioquia UdeA, Calle 70 No. 52-21, Medellín, Colombia, sergio.agudelo@udea.edu.co

ABSTRACT: Electro-osmotic consolidation is a ground improvement technique in which a DC voltage is applied to the soil via electrodes, in order to drain the water contained in the pores increasing the effective stress, and thus improving the geotechnical properties of the soil. The technique increases the shear strength, reduces the compressibility, and changes the chemical composition of the saturated soft clayey and silty soils to which it can be applied. Electro-osmotic consolidation has been successfully applied in different projects worldwide. This paper presents the development of a new electro-osmotic consolidation apparatus built at Universidad de Antioquia. Tests were carried on a reconstituted clay sample and the results show effective soil improvement, measured as changes in the geotechnical properties of the clay.

Keywords: electro-osmosis; consolidation; soft soils; soil improvement; laboratory testing.

1. Introduction

It is becoming increasingly difficult to find sites with favorable geotechnical conditions for constructive purposes. Hence, the implementation of works during and after construction to prevent failures in the soil-structure system is a decisive factor. The characteristic of geomaterials, natural conditions and anthropic interventions may lead to apply a soil improvement [1].

The main objective of the soil treatment is to improve the geotechnical properties of the material, i.e. increase the shear strength and reduce the compressibility, thus raising the bearing capacity of the foundation. The simplest and most effective way to achieve this is to reduce the pore water pressure (PWP). Consequently, a wide variety of improvement methods focus on removing water from the system [2]. The suitability of each method depends of requirements of the project, such as location, type, size, depth, thickness, stratification, permeability of the material, groundwater levels, possible damages caused by the application of the method and the cost of installation and operation [1]. The main limitation of these methods is the low permeability of the soil, which is a distinctive features of clayey materials.

Clays exhibit a behavior associated with their complex compositional and structural characteristics [3]. The different mineral constituents can be stacked in tetrahedral or octahedral laminated structures [4], which can be combined in various arrangements that can form different mineral groups [5]. Its high porosity condition controls the storage capacity and water flow, determining the consolidation speed as a product to the external load imposition [6]. In addition, the presence of water molecules create physical and mechanical responses in the material, because it acts as an interlaminar ionic solution with accessible counterions for the clayey surfaces [7], modifying the properties of the electric double layer [8].

Electro-osmosis is a ground improvement technique in which the drainage of the water contained in the material is promoted by pressure differences, through the application of an electric current [1]. The flow is impeded at the anode and attracted to the cathode, as response to an electrochemical gradient generation in the soil-water system. Consequently, consolidation is accelerated and material strength increase is achieved [9], improving the compressibility conditions and chemical composition [10]. Since dehydration is its predominant effect, the method is considered a hydraulic modification technique [11].

The development of the electrokinetic principles, under which electro-osmosis is governed, had its origins at the early nineteenth century through to the contributions and experiments of researchers such as F. F. Reuss in 1808, G. Wiedemann in 1852 and G. Quincke in 1859 [12]. Later, in 1879, Helmholtz presented the analytical development of electrokinetics, modified by Pellat in 1904 and by Smoluchowski in 1921 [13]. By the 1930s, Casagrande performed the first successful stabilizations of soft fine-grained soil using the technique [14]–[16]. Afterwards, successful field applications were documented for the stabilization of excavation [17]–[19], dam construction [20], slope stabilization [21], embankment control [22], increment of friction capacity in piles [23], [24], and foundation treatment [18], [25]–[27]. In recent decades, results of the technique for chemical remediation of contaminated soils have been reported [28], increase of safety conditions for tailings dams [29], and field test [30], [31]. However, the method has not been widely implemented, due to the numerous geotechnical, hydraulic, chemical, and electrical variables that must be controlled in the process.

To investigate the improvement of the mechanical properties of clays by means of the electro-osmotic technique, several researchers have designed consolidation apparatus with different geometries, materials, load application types, and drainage methodologies. Many of these are modified oedometers and triaxial apparatus [32]–[35]. Other devices have been designed based on the load application mode, considering direct current, intermittent current [36]–[40], mechanical pressure, chemical precipitation [41]–[46], pneumatic pressure [43], [47]–[51], triaxial load [33]–[35], thermal gradients [15] and vacuum pressure [52]. In the geometric design of the cells the electrodes material has also been considered, being common the use of perforated plates [17], [48], [53], discs [54], [55], tubular electrodes [36], rods [56], [57], pipes [39], wires [40], meshes [36], [37], [58], springs [59], electrokinetic geosynthetics (EKG) [44], [46], electrical vertical drains (EVD) [9]. Another determining factor for the geometric configuration of the devices has been the flow patterns according to the drainage boundaries for consolidation, some of the configurations selected are side drainage [15], [47], gravitational [36], through upper contours [17], [57], [60] and lower contours individually [34], [59] or simultaneously [55], [61], or across the electrodes [38], [39].

In order to study variables involved in the electro-osmotic consolidation process, the design of a new electro-osmosis consolidation cell is presented. The sample preparation procedure is detailed and the working conditions of the new cell are validated using a commercial soft clay with plastic characteristics.

2. Electro-osmotic consolidation testing apparatus

In order to analyze the consolidation mechanisms in soils by applying the electro-osmotic technique, a cell that allows the measurement of geotechnical parameters and electrochemical effects was designed. Figure 1 show a scheme of the apparatus described.

The cell was built in a carbon steel pipe (SCH 40) with a 155 mm diameter and 600 mm length, considering the high rate in volume reduction provided by the technique. The material used can withstand the high pressures that need to be applied without suffering deformations that may affect the consolidation process. The system is divided into three cylinders, each one being restrained laterally to two vertical tie rod. The lower compartment is used to consolidate the sample, the middle compartment is used to extrude the control samples at the start of the process and the upper compartment provides sturdiness and provides sealing conditions.

The base of the cell, also in carbon steel, has a 250 mm diameter and is 25 mm thick. It has a central compartment that holds a porous stone to allow water drainage with 36 mm in diameter and 7 mm thick, connected to radial channels 4 mm thick. Correspondingly, the upper piston that transfers the load into the sample, is provided with two compartments for porous stones with similar dimensions to the one at the base. These compartments are located between the electrodes at a spacing of 60 mm. Each drainage channel is equipped with 3.175 mm ball valves to control the drainage path in order to analyze different cases. The piston is a carbon steel plate 155 mm in diameter and 12.7 mm thick. It is fitted hermetically with a 2.5 mm radius O-ring, allowing vertical displacement in the cylinder whilst the load is applied, using the electrodes as displacement axis. The pieces were machined with a CNC tool programmed using specification from a 3D CAD model. Two cylindrical stainless steel rods were used as electrodes with 8 mm diameter and spaced 120 mm. To improve drainage or to allow the injection of electrochemical solutions, perforated pipes or electric drains could be used as electrodes. Figure 2(a) details the configuration of the electro-osmotic consolidation cell.

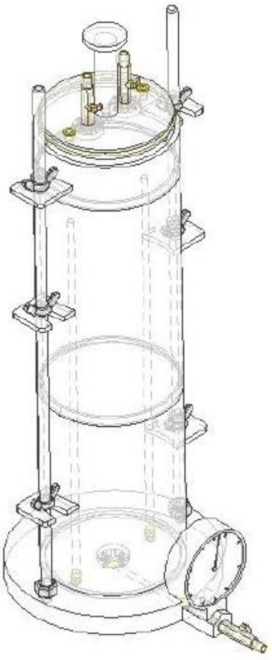
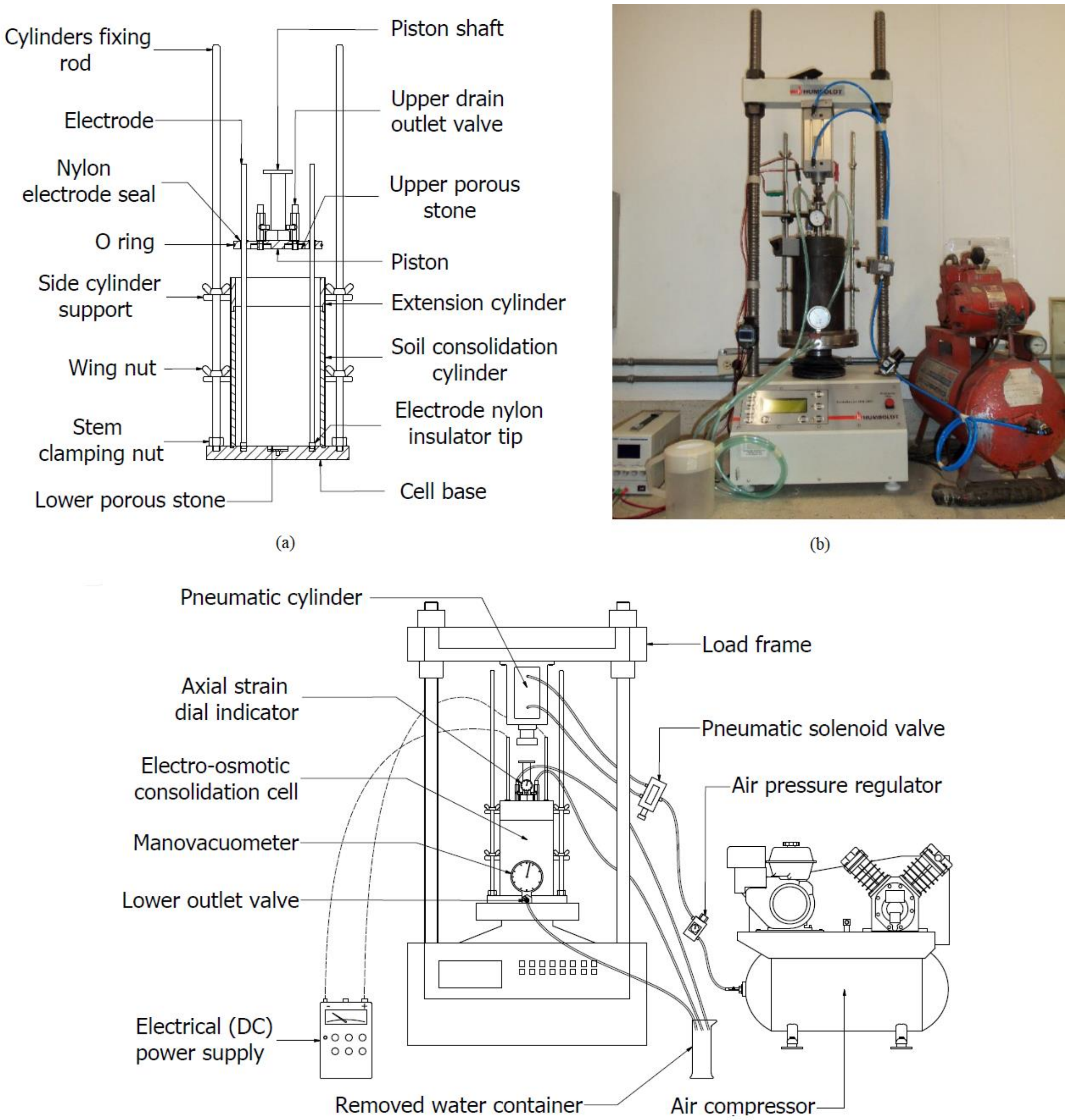


Figure 1. Electro-osmotic consolidation cell scheme.

Figure 2 (b) and (c) show the experimental setup. The pressure gradients in the soil are generated using a combined loading system capable of applying mechanical and electrical loads. For the mechanical load increments, a loading frame with adjustable height was used. A double acting pneumatic cylinder with a 76.2 mm stroke and an internal diameter of 76.2 mm was fitted to the frame. The airflow was supplied by means of a compressor controlled by a solenoid valve and an air pressure regulator. The direct current was provided using an adjustable power supply. The cell was instrumented using a manovacuometer placed at the end of the lower drainage line to measure pore water pressure when a test is conducted with top drainage. An axial strain dial indicator was used to measure deformations.



(a)

(b)

(c)

Figure 2. (a) Electro-osmotic cell configuration, (b) picture of the experimental set up and (c) experimental setup.

3. Testing procedure

3.1. Clay description

The soil used on the test was a natural clay of plastic characteristics, supplied by Insumos Industriales Corona - Suministros de Colombia S.A.S. Table 1 shows the result of the soil characterization tests. The soil is classified as a Fat clay (CH) in the Unified Soil Classification System (USCS). Table 2 presents the chemical species in the material, determined using an X-ray fluorescence analysis provided by the supplier.

Table 1. Soil physical properties.

Properties	Standard	Value
Water content	ASTM D2216-19 [62]	2.7%
Specific gravity	ASTM D854-14 [63]	2.68
Liquid limit		58%
Plastic limit	ASTM D4318-17 [64]	30%
Plasticity index		28%
USCS classification	ASTM D2487-17 [65]	CH
Clay content		60.00%
Silt content	ASTM D422-63 [66]	36.75%
Retained on No. 200		3.25%

Table 2. Chemical composition of the clay.

Species	Value
SiO_2	55% - 63%
Al_2O_3	23% - 28%
Fe_2O_3	3% Max
TiO_2	3% Max
CaO	< 0,3%
MgO	< 0,6%
Na_2O	N.D
K_2O	< 1%

3.2. Sample preparation

The clay sample was prepared following the recommendations by Burland [67] for reconstituted samples, so as to work with the intrinsic properties of the material, which are inherent to the soil and independent of its natural state.

To this end, the soil was thoroughly mixed with at a water content of 1.25 times the liquid limit, which corresponds to a water content of 72.5% for the chosen clay. The sample was then placed in layers of approximately 100 mm using a tamping rod to remove significant air bubbles. Whilst the cell was being filled, samples were taken to verify the water content, given the nature of the clay may condition how fast the water molecules are accepted, thus being possible that the soil reconstituted in this manner may not be saturated at the start of the test [68]. After the cell was filled, the piston was placed avoiding any water leaks from the system and verify the instrumentation. Finally, the loads necessary for the reconstitution were applied.

3.3. Sample reconstitution and electro-osmotic consolidation

The testing procedure comprised two phases: (1) the reconstitution of the sample by means of mechanical loading and (2) the application of the electrical load to generate the electro-osmotic mechanism in the soil sample. The consolidation of the sample was done under a double drainage condition.

Maintaining the intrinsic properties of the clay requires load increments that have a Load Increment Ratio (LIR) equal to or greater than unity [67]. Hence, the loading schedule used consisted of loads that doubled the total axial stress on the soil [69]. To guarantee the applied loads magnitudes on the sample, oil was used to lubricate the walls of the mold, minimizing the friction between the O-ring and the cylinders walls, thus allowing the correct sliding piston. Initially, a low magnitude stress was used to act as a preload and, at the same time, it allowed for an initial response of the compressor attached to the system. The load magnitudes used were 8.3, 12.5, 25.0 50.0 y 100.0 kPa of total stress. For each load increment, settlement readings were taken at 0.1, 0.25, 0.5, 1.0, 2.0, 4.0, 8.0, 15.0, 30.0 min, 1.0, 1.5, 2.0, 4.0, 8.0, 24.0 h and then every 24 h until 100% of the primary consolidation is reached. Once the maximum load is applied, an electrical potential gradient of 50 V/m with variable current was applied, as recommended by Mitchell [70], whilst the 100 kPa mechanical load was maintained.

4. Results and discussion

Table 3 presents the settlement achieved under each load increment. The sample located in the bottom cylinder and subjected to the consolidation process had an initial height of 288.60 mm and by the end of the process, it underwent a settlement of 69.27 mm during the 27360 min (19 days) that the test lasted. Of the total settlement, 43.46 mm correspond to the electro-osmotic improvement that was applied during 18720 min (13 days). The test results are summarized in the Log-time – settlement curves shown in Figure 3.

As can be seen, for all the load increments there was an instant volume reduction in the first one to two minutes; which can be explained by the immediate flow of water out of the sample as a response to the pore water pressure increment generated by the load imposed. Next, for the 8.3, 12.5, and 25.0 kPa load increments, there is a two to three minutes plateau in the curve, in which the soil does not suffer any settlement. This may be explained by the reconstitution process in which the internal structure of the soil is being formed. Afterward, the primary consolidation process continues. For the load increments of 50.0, 100.0 kPa, and 100 kPa + electro-osmotic load (EO), the aforementioned plateau is not present and the behavior follows a typical consolidation curve.

Reviewing the Log-time – settlement curves for the load increments of 100 kPa and 100 kPa + EO, a significant deformation was achieved in the first two minutes for both loads. However, when the EO load was applied the settlement increased by 151% when compared to the load with no electrical current, going from 6.48 mm to 16.26 mm (Table 3). This result shows the efficiency achieved by using the electro-osmotic loads.

Table 3. Soil sample deformations due to each load increment.

Applied stress σ (kPa)	Settlement S (mm)	Sample Height H (mm)	Voids Height Hv (mm)	Void Ratio e (adim)
0.0	0.00	288.60	195.17	2.09
8.3	0.51	288.09	194.66	2.08
12.5	0.69	287.41	193.98	2.08
25.0	1.83	285.58	192.15	2.06
50.0	2.64	282.94	189.51	2.03
100.0	6.48	276.46	183.03	1.96
100 + EO	16.26	260.20	166.77	1.79

Using the Log of Time Method [69] to analyze the Log-time – settlement curves, the times to reach 50% of the consolidation (t50) were determined as shown in Figure 3. The magnitude of t50 is proportional to the drainage frontier and decreases with an increase in coefficient of consolidation, hence when the load is increased the required consolidation times are smaller. This behavior is in agreement with what was expected for the volume reduction of a soil, a gradual reduction in consolidation time as the effective stress increases, verifying the correct operation of the cell.

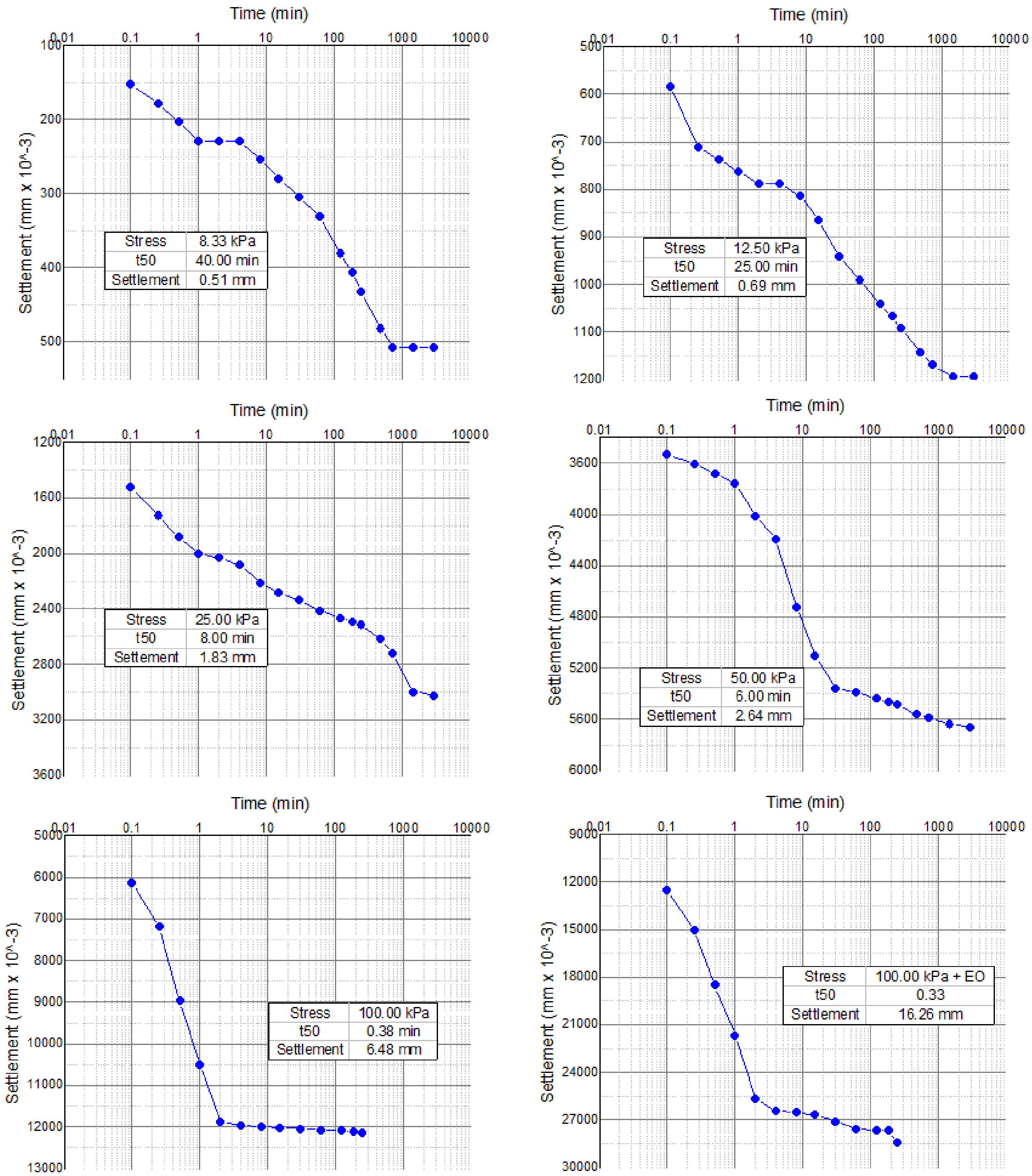


Figure 3. Log-time – settlement curve for the loads applied.

On the other hand, the compressibility curves for the mechanical and electrical loads (Figure 4), show that the electro-osmotic consolidation does not affect the intrinsic properties of the clay, being the compressibility one of these properties [67]. In this case, the preconsolidation pressure obtained was 50 kPa.

Table 4 presents the values for the coefficients of compressibility, consolidation, volume compressibility and permeability for the 50% of consolidation. The increase of the effective stress leads to an increment in the coefficient of compressibility. At the End of Primary consolidation by electro-osmotic loading there was a 151% increase in the coefficient of compressibility with respect the value for conventional consolidation. The settlement reached during the electro-osmotic process correspond to a 57.2% of the total deformation, indicating a reduction in the drainage frontier during this phase of the process, thus reducing the coefficient of consolidation considerably. In conventional consolidation, the coefficient of permeability reduces gradually along with the void ratio reduction. However, when the electrical current is applied to the soil, an increase in the flow of water occurs due to the electro-osmotic permeability, which is added to the hydraulic permeability to estimate the flow rate in the soil. This results verify that the electro-osmotic permeability is higher than the hydraulic permeability, as was proposed by Grosso et al. [42].

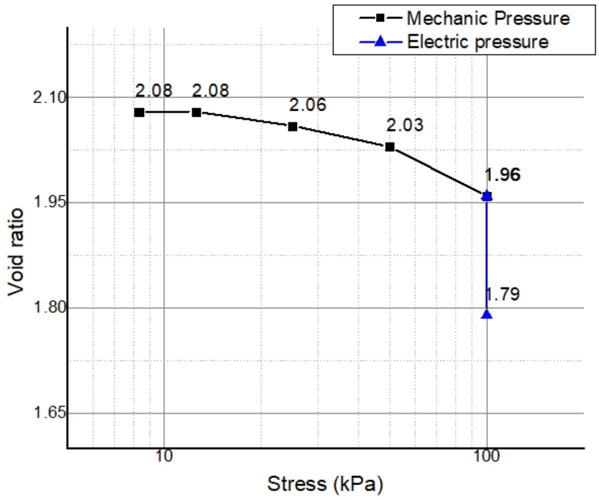


Figure 4. Compressibility curves for conventional and electro-osmotic consolidation.

Table 4. Coefficient values for the loading process.

	Coefficient of			
Applied stress σ (kPa)	Compressibility av (m2/kN)	Consolidation Cv (cm2/min)	Volume compressibility mv (m2/N)	Permeability K (cm/min)
0	-	-	-	-
8.33	0.00065	4.09	0.00021	0.0009
12.50	0.00176	7.40	0.00057	0.0042
25.00	0.00157	22.95	0.00051	0.0117
50.00	0.00113	26.28	0.00037	0.0097
100.00	0.00139	396.23	0.00046	0.1814
100+EO	0.00348	404.18	0.00118	0.4754

It is necessary to clarify the calculation of the coefficient of volume compressibility. It entails considering a stress increment of 50 to 100 kPa. Mathematically, there is no change in the applied stress between 100 kPa and 100+EO kPa. However, applying electrical loads causes a change in the stress state. This changed is evidenced in the void ratio reduction and the expulsion of water.

In future studies, the use of pore water pressure could be implemented in the calculation of permeability and the coefficient of volume compressibility.

Figure 5 shows the variations of the water content in the vertical and horizontal directions in relation the electrodes location. The average initial water content was 72.42%. Near the cathode (negative terminal) the water content reduction was smaller than near the anode (positive terminal) throughout the entire sample. The water content at the center of the sample, i.e. midway between the cathode and the anode, also had a reduction that was lower than near the anode but higher than near the cathode. The highest water reduction occurred at the top of the sample near the anode, with a drop of approximately 26%, as the water at this point is closer to the drainage frontier. These results indicate a flow of water from the anode towards the cathode, as it is to be expected for this type of treatment.

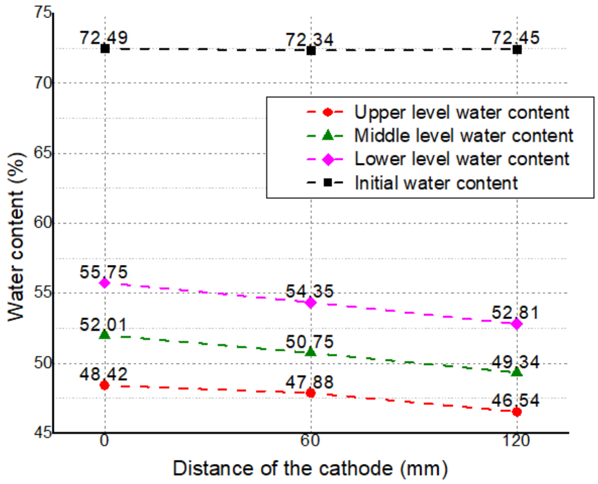


Figure 5. Water content profile at different depths.

With regards to the pH, Figure 6 shows that under the initial conditions the average value was 5.02, being an acidic sample. At the end of the test, the pH valued had increased near the cathode (negative terminal) and reduced near the anode (positive terminal). This behavior contradicts what Grosso et al. [42] argued, as the authors said that electro-osmotic consolidation should globally reduce the pH near cathode and increase near the anode. This discrepancy can be explained by the detachment of oxidative-reductive ions due to the corrosion of the cathode steel rod, which did not occurred on the anode steel rod.

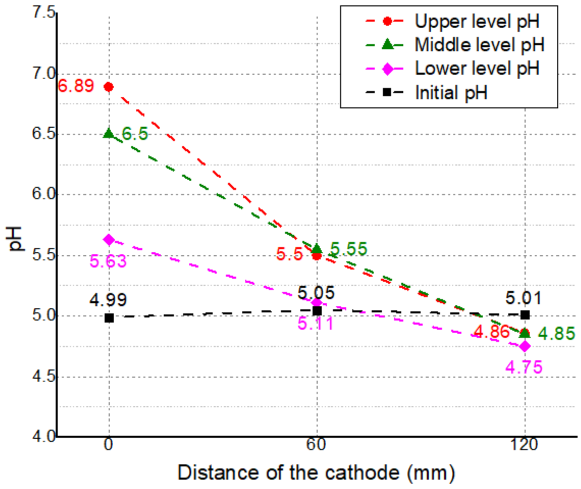


Figure 6. pH variation profile.

5. Conclusions

A new electro-osmotic consolidation cell was successfully developed. It will provide useful information on the behavior of the physical, mechanical, chemical and electrical parameters that intervene in the efficiency of the technique.

The apparatus has a cylindrical configuration for the sample reconstitution process and the consolidation of the sample. It is hermetically sealed to quantify the water flow and the deformations associated to the stress increments. The loading system is comprised by a load frame, a pneumatic cylinder for the mechanical loads and an adjustable power supply for the electrical loads.

The procedure employed to verify the correct operation of the new apparatus consisted in applying an array of five mechanical loads (8.3, 12.5, 25.0, 50.0, y 100.0 kPa) to quantify the consolidation of the sample. Later, a mechanical load of 100 kPa combined with an electrical potential gradient of 50 V/m with variable current was applied.

The process provided deformation results for the applied loads, showing 151% higher settlement values for the combined mechanical + electrical load when compared to the mechanical only load.

The electro-osmotic permeability contribution to the settlement and to the total permeability of the soil was also reviewed.

The water content variation is higher towards the drainage frontier near the cathode, indicating that the flow of water is from the anode towards the cathode, as expected for this technique.

The pH of the soil increased near the cathode and reduced near the anode; a situation that can be explained by the corrosion that occurred around the steel rod of the former, whilst no corrosion was present at the latter.

Acknowledgments

The authors would like to acknowledge the financial support provided by Universidad de Antioquia under the Undergraduate Final Year Project Support Fund (Minute No. PR 15-2-07) of the Research Development Committee – CODI; as well as the technical and financial support provided by the research groups GeoResearch International – GeoR and Grupo de Energía Alternativa – GEA from the same university.

The authors are also grateful to Mr. Julio Ramirez for the assistance provided.

References

[1] J. Han, *Principles and Practice of Ground Improvement*. Hoboken, New Jersey, USA, 2015.

[2] P. G. Nicholson, *Soil Improvement and Ground Modification Methods*. Oxford, 2015.

[3] T. Vakalova, V. Pogrebenkov, V. Vereshagin, T. Khabas, and I. Revva, "Optimising rational chemical analysis for quantitative determination of the composition of clay in soils," *Appl. Clay Sci.*, vol. 163, pp. 153–163, 2018.

[4] J. K. Mitchell and K. Soga, *Fundamentals of Soil Behavior*, 3rd ed. Hoboken: John Wiley & Sons, 2005.

[5] G. Sposito, *The Chemistry of Soils*, Second. New York, Estados Unidos: Oxford University Press, Inc, 2008.

[6] O. Uyanik, "Estimation of the porosity of clay soils using seismic P- and S-wave velocities," *J. Appl. Geophys.*, vol. 170, pp. 1–8, 2019.

[7] M. Holmboe, S. Wold, and M. Jonsson, "Porosity investigation of compacted bentonite using XRD profile modeling," *J. Contam. Hydrol.*, vol. 128, pp. 19–32, 2012.

[8] G. Sposito, N. T. Skipper, R. Sutton, S.-H. Park, A. K. Soper, and J. A. Greathouse, "Surface geochemistry of the clay minerals," in *Proceedings of the National Academy of Sciences of the United States of America*, 1999, vol. 96, no. 7, pp. 3358–3364.

[9] A. R. Estabragh, M. Naseh, and a. a. Javadi, "Improvement of clay soil by electro-osmosis technique," *Appl. Clay Sci.*, vol. 95, pp. 32–36, 2014.

[10] A. Rittirong and J. Shang, "Electro-Osmotic Stabilization," in *Ground Improvement — Case Histories*, 1st ed., vol. 3, B. Indraratna and J. Chu, Eds. Kidlington, England: Elsevier, 2005, pp. 967–996.

[11] M. R. Hausmann, *Engineering Principles of Ground Modification*. Singapore, 1990.

[12] S. Wall, "The history of electrokinetic phenomena," *Curr. Opin. Colloid Interface Sci.*, vol. 15, pp. 119–124, 2010.

[13] S. Shenbagavalli and S. Mahimairaja, "Electro kinetic remediation of contaminated habitats," *African J. Environ. Sci. Technol.*, vol. 4, no. 13, pp. 930–935, 2010.

[14] L. Casagrande, "Electro-Osmosis in soils," *Géotechnique*, vol. 1, no. 2, pp. 159–177, 1949.

[15] D. H. Gray and J. K. Mitchell, "Fundamental aspects of electroosmosis in soils," *J. Soil Mech. Found. Div. Proc. Am. Soc. Eng.*, vol. 93, no. SM-6, pp. 209–236, 1967.

[16] M. Karim, "Electrokinetics and soil decontamination: concepts and overview (Review)," *J. Electrochem. Sci. Eng.*, vol. 4, no. 4, pp. 297–313, 2014.

[17] L. Bjerrum, J. Moum, and O. Eide, "Application of Electro-Osmosis to a Foundation Problem in a Norwegian Quick Clay," *Géotechnique*, vol. 17, no. 3, pp. 214–235, Sep. 1967.

[18] C. Caron, "Applications et essais dans le domaine de l'électrosomose des terrains sableux et argileux," *Bull. Tech. la Suisse Rom.*, vol. 1, p. 1, 1968.

[19] E. De Beer and Wallays, "Application des drains Kjellman-Franki et de l'électroosmose," *La Tech. des Trav.*, vol. 41, no. 3–4, pp. 89–102, 1965.

[20] C. A. Fetzer, "Electro-osmotic stabilization of West Branch Dam," *J. Soil Mech. Found. Div. Proc. Am. Soc. Eng. ASCE*, vol. 93, no. 4, pp. 85–106, 1967.

[21] M. H. Wade, "Slope Stability by Electro-Osmosis," in *Proceedings of the 29th Canadian Geotechnical Conference*, 1976, p. Sección 10, 44-66.

[22] B. A. Chappell and P. L. Burton, "Electro-osmosis applied to unstable embankment," *J. Soil Mech. Found. Div. Proc. Am. Soc. Eng. ASCE*, vol. 101, no. 8, pp. 733–740, 1975.

[23] L. G. Soderman and V. Milligan, "Capacity of Friction Piles in Varved Clay Increased by Electro-Osmosis," in *Proceedings Fifth International conference on Soil Mechanics and Foundation Engineering*, 1961, pp. 143–147.

[24] V. Milligan, "First application of electro-osmosis to improve friction pile capacity-three decades later," *Proc. Inst. Civ. Eng. - Geotech. Eng.*, vol. 113, no. 2, pp. 112–116, 1995.

[25] S. C. Dearstyne and G. J. Newman, "Subgrade stabilization under an existing runway," *J. Aerosp. Eng. ASCE*, vol. 89, no. AT1, pp. 1–8, 1963.

[26] S. Sridharan, "Application of electrokinetics for piles in black cotton soil," *Indian Concr.*, vol. 46, no. 6, pp. 245–248, 1972.

[27] I. W. Johnston and R. Butterfield, "The influence of electro-osmosis on metallic piles in clay," *Géotechnique*, vol. 30, no. 1, pp. 17–38, 1980.

[28] A. T. Lima, P. J. Kleingeld, K. Heister, and J. P. Gustav Loch, "Removal of PAHs from contaminated clayey soil by means of electro-osmosis," *Sep. Purif. Technol.*, vol. 79, no. 2, pp. 221–229, 2011.

[29] N. C. Lockhart, "Electro-osmotic dewatering of fine tailings from mineral processing," *Int. J. Miner. Process.*, vol. 10, no. 2, pp. 131–140, 1983.

[30] K. Y. Lo and K. S. Ho, "The effects of electroosmotic field treatment on the soil properties of a soft sensitive clay," *Can. Geotech. J.*, vol. 28, pp. 763–770, 1991.

[31] K. Y. Lo, K. S. Ho, and I. I. Inculet, "Field test of electroosmotic strengthening of soft sensitive clay," *Can. Geotech. J.*, vol. 28, no. 1, pp. 74–83, Feb. 1991.

[32] J. K. Mitchell and T.-Y. Wan, "Electro-Osmotic Consolidation - Its effects on soft soils," in *Proceedings of the 9th International Conference on Soil Mechanics and Foundation Engineering ICSMFE*, 1977, p. Vol 1, 219-224.

[33] M. W. Bo, V. Choa, and X. Q. Zeng, "Laboratory investigation on electro-osmosis properties of Singapore marine clay," *Soils Found.*, vol. 41, no. 5, pp. 15–23, 2001.

[34] S. Jayasekera, "Electroosmotic and hydraulic flow rates through kaolinite and bentonite clays," *Aust. Geomech.*, vol. 39, no. 2, pp. 79–86, 2004.

[35] V. Jeyakanthan, C. T. Gnanendran, and S.-C. R. Lo, "Laboratory assessment of electro-osmotic stabilization of soft clay," *Can. Geotech. J.*, vol. 48, no. 12, pp. 1788–1802, 2011.

[36] J. Q. Shang and K. Y. Lo, "Electrokinetic dewatering of a phosphate clay," *J. Hazard. Mater.*, vol. 55, pp. 117–133, 1997.

[37] S. Micic, "Electrokinetic strengthening of soft marine sediments," University of Western Ontario, 1998.

[38] E. Mohamedelhassan and J. Q. Shang, "Effects of electrode materials and current intermittence in electro-osmosis," *Proc. ICE - Gr. Improv.*, vol. 5, no. 1, pp. 3–11, 2001.

[39] M. H. El Naggar and S. A. Routledge, "Effect of electro-osmotic treatment on piles," *Proc. ICE - Gr. Improv.*, vol. 8, no. 1, pp. 17–31, 2004.

[40] L. Hu, H. Wu, and Q. Wen, "Electro-osmotic consolidation: Laboratory tests and numerical simulation," in *Proceedings of the 18th International Conference on Soil Mechanics and Geotechnical Engineering*, 2013, pp. 231–234.

[41] N. Otsuki, W. Yodsudjai, and T. Nishida, "Feasibility study on soil improvement using electrochemical technique," *Constr. Build. Mater.*, vol. 21, no. 5, pp. 1046–1051, May 2007.

[42] B. Grosso, M. Cigagna, P. P. Manca, and P. Tronci, "The use of electroosmotic technique to improve safety conditions of abandoned tailing dams," in *16th International Symposium on Mine Planning and Equipment Selection*, 2007, pp. 373–387.

[43] S.-C. Chien, C.-Y. Ou, and Y.-C. Lee, "A novel electroosmotic chemical treatment technique for soil improvement," *Appl. Clay Sci.*, vol. 50, no. 4, pp. 481–492, Dec. 2010.

[44] S. A. Ahmad Tajudin, "Electrokinetic stabilization of soft clay," University of Birmingham, 2012.

[45] G. A. Megur and P. G. Rakaraddi, "A study on stabilization of soil y electro kinetic method," *Int. J. Res. Eng. Technol. IJRET*, vol. 03, no. 06, pp. 104–109, 2014.

[46] A. Arutzelvam, "Soft Clay Stabilization Using Electro Kinetic Process," *Int. J. Eng. Technol. Sci. - IJETS*, vol. I, no. II, pp. 50–55, 2014.

[47] M. Arnold, "Laboratory determination of the coefficient of electro-osmotic permeability of a soil," *Géotechnique*, vol. 23, no. 4, pp. 581–588, 1973.

[48] G. Lefebvre and T. V. Pavate, "A study on electro-osmotic consolidation of soft clays," in *Third International Conference on Case Histories in Geotechnical Engineering*, 1993, pp. 1131–1137.

[49] C. Kit, "Design and Modelling of Electro-osmotic Dewatering," Newcastle University, 2006.

[50] K. Yusof and A. Marto, "Implementation of electro-osmotic consolidation test through laboratory approach," in *Proceedings of the 9th International Conference on Geotechnical and Transportation Engineering GEOTROPIKA*, 2013.

[51] K. Yusof, F. Ahmad, M. Al Bakri Abdullah, and M. Mohd Tahir, "Effects of Electro Osmotic Consolidation in South West of Johor: Small Laboratory Scale," *Mater. Sci. Forum*, vol. 803, no. August, pp. 255–264, Aug. 2015.

[52] J. Peng, H. Ye, and A. N. Alshawabkeh, "Soil improvement by electroosmotic grouting of saline solutions with vacuum drainage at the cathode," *Appl. Clay Sci.*, vol. 114, pp. 53–60, 2015.

[53] T.-Y. Wan and J. K. Mitchell, "New apparatus for consolidation by electro-osmosis," *J. Geotech. Eng. Div. Proc. Am. Soc. Civ. Eng.*, vol. 101, no. GT5, pp. 503–509, 1975.

[54] K. Y. Lo, I. I. Inculet, and K. S. Ho, "Electroosmotic strengthening of soft sensitive clays," *Can. Geotech. J.*, vol. 28, no. 1, pp. 62–73, Feb. 1991.

[55] J. Q. Shang and K. S. Ho, "Electro-osmotic consolidation behavior of two Ontario clays," *Geotech. Eng.*, vol. 29, no. 2, pp. 181–194, 1998.

[56] D. Tjandra and P. S. Wulandari, "Improving marine clays with electrokinetics method," *Civ. Eng. Dimens.*, vol. 9, no. 2, pp. 98–102, 2007.

[57] C. M. A. R. Melo, S. Tibana, F. A. Saboya, R. M. Reis, V. M. Del Aguila, and E. Z. Silva, "Physical models consolidation by electroosmosis," in *14th Pan-American Conference on Soil Mechanics and Geotechnical Engineering, Geo-Innovation Addressing Global Challenges*, 2011.

[58] Y. Guo, "Electrokinetic Dewatering of Oil Sands Tailings," University of Western Ontario, 2012.

[59] K. Yusof, "Composite foundations on Malaysian soft clay soil : Applications of innovative techniques," University of Leeds, 2012.

[60] T.-Y. Wan and J. K. Mitchell, "Electro-osmotic consolidation of soils," *J. Geotech. Eng. Div. ASCE*, vol. GT5, no. 102, pp. 473–491, 1976.

[61] J. Q. Shang, K. Y. Lo, and K. M. Huang, "On factors influencing electro-osmotic consolidation," *Geotech. Eng.*, vol. 27, no. 2, pp. 23–36, 1996.

[62] American Society for Testing Materials - ASTM, "ASTM D2216-19 Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass." ASTM International, West Conshohocken, PA, 2019.

[63] American Society for Testing Materials - ASTM, "ASTM D854-14 Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer." ASTM International, West Conshohocken, PA, 2014.

[64] American Society for Testing Materials - ASTM, "ASTM D4318-17e1 Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils." ASTM International, West Conshohocken, PA, 2017.

[65] American Society for Testing Materials - ASTM, "ASTM D2487-17 Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System)." ASTM International, West Conshohocken, PA, 2017.

[66] American Society for Testing Materials - ASTM, "ASTM D422-63(2007)e2 Standard Test Method for Particle-Size Analysis of Soils." ASTM International, West Conshohocken, PA, 2007.

[67] J. B. Burland, "On the compressibility and shear strength of natural clays," *Géotechnique*, vol. 40, no. 3, pp. 329–378, Sep. 1990.

[68] E. Mohamedelhassan and J. Q. Shang, "Vacuum and surcharge combined one-dimensional consolidation of clay soils," *Can. Geotech. J.*, vol. 39, pp. 1126–1138, 2002.

[69] American Society for Testing Materials - ASTM, "ASTM D2435 / D2435M -11 Standard Test Methods for One-Dimensional Consolidation Properties of Soils Using Incremental Loading." ASTM International, West Conshohocken, PA, 2011.

[70] J. K. Mitchell, "Soil lmprovement - State of the Art Report," in *Proceedings of the 10th International Conference on Soil Mechanics and Foundation Engineering ICSMFE*, 1981, p. Vol 4, 509-565.