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## IMPLEMENTATION OF ELECTRO-OSMOTIC CONSOLIDATION TEST THROUGH LABORATORY APPROACH

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Soft clay is cohesive soil having water content higher than its liquid limit. It is a type of fine-grained soils which changed volume when permanently loaded in a process called 'consolidation'. Due to that, the occurrence of unstable and highly differential of settlement under a structure is a common phenomenon. The improvements are needed for this type of soil before any construction takes place to avoid ground or structural failure in the future. The basic concepts of soil improvement include densification, cementation, reinforcement, soil modification or replacement, drainage and other water content control. Ground modification played a very essential role in many Geotechnical projects. One of the methods to improve this soil is using electro-osmotic consolidation. The electro-osmotic consolidations method will alter the hydraulic conductivity of the soil, hence improved the soil with the process of discharging the water within the soil particles. The method of this treatment depends on applied voltage and electrode material and the time of the treatment depends on the soil properties. This paper demonstrates the implementation of electro-osmotic process in small laboratory approach and synthesized the effect of void ratio and the coefficient of volume compressibility due to electro-osmotic process. A sample with one terminal positive (anode) surrounded with eight terminal negative (cathode) was tested to implement the electro-osmotic consolidation on the laboratory approach. The sample that was tested for 24 hours on phase 2, recorded 0.49 mm of vertical readings with 5 Volts as the applied voltage, develops a reduction in void ratios, low in water content and high in stiffness. Due to the significant stiffening effect at the end of 50 kPa vertical load application, this method is seen to have potential applications in improving the soft soils in situ.

Keywords: soft clay, electro-osmotic, consolidation, soil improvement.

### Introduction and Background of Study

When structures are built on saturated ground, the load is presumed to be held initially by incompressible water within the soil. Because of additional load on the soil, water will tend to be extruded from voids in the soil, causing a reduction in void volume and settlement of a structure. In soils of high permeability (coarse-grained soils), this procedure takes a short time interval for completion, with the result that almost all of the settlement has passed by the time construction is complete. However,

in soils of low permeability (fine-grained soils, particularly clayey soils), the process takes a long time interval for completion, with the result that strain occurs very slowly. Thus, settlement takes place slowly and continues over a long period of time.

The phenomenon of compression due to very slow extrusion of water from the voids in a fine-grained soil as a result of increased loading (such as the weight of a structure of a soil) is known as consolidation. Associated settlement is referred to as consolidation settlement. It is important to be able to predict both the rate and magnitude of the consolidation settlement of the structures. The method presented, procedures for determining the magnitude and rate of consolidation of soil when it is restrained laterally and drained axially while subjected to incrementally apply, controlled-stress loading.

In general, theory of consolidation deals with the response of soil systems to impose load and predicts stresses and displacements of the loaded soil as a function of distance and time. This theory, since its introduction by Terzaghi, has formed the foundation of modern Geotechnical engineering. The concept is central to the practice of Geotechnical engineering where the interaction of land and water dominates. Although consolidation is used for estimating settlements, it has also played key roles in the analysing stability of slopes, design of piled foundations, laboratory tests. An extensive study has been undertaken to study, characterize and predict the behaviour of Soft clay. This was undertaken so that future structures can be designed and constructed safely and economically.

For many years, civil engineers are faced with a great challenge to design structures on soft compressible soils which include soft clay, silt and peat foundations. Consolidation of water-saturated, fine-grained soil occurs very slowly because the low permeability of these soils impedes the escape of pore water from the soil voids. Such soils have poor drainage and strength properties. Even under large temporary surcharge loads, settlement can take years because of this slow water movement and the great distance the water must move to exit the soil.

To increase the soil stability based on the requirement of economic cost, there are few numerous methods of soil improvement methods according to the geological conditions, soil types and environments may be implemented. Extensive studies regarding the ground improvements were written in papers such as Eggestad, and Jamiolkowski et al in 1983. Research paper by Brand and Brenner in 1981 discusses the improvement of cohesionless soil, while Jamiolkowski et al. presented the studies on the precompression and speeding up the consolidation process. Finally, the improvement of the cohesion soil was studied by Eggestad in 1983.

The ground improvements within the soil types are divided into two parts, i.e., for coarse materials and fine materials. Electro osmotic falls in fine material and categorised under a hydraulic modification. The theoretical of electro osmosis was fully developed by Reuss in 1809 where he observed the water flow in soils as a result

of a direct electric current passing through it. Then followed by few famous researchers, which they presented a study where the electro osmosis was being applied in the field as to improve the problematic field conditions. Their studies were presented in journals and conference papers such as Casagrande in 1949 and 1952, Casagrande et al. in 1961, Soderman and Milligan in 1961, Bjerrum et al. in 1967, Fetzer in 1967, Mitchell in 1991, Chappell and Burton in 1975, Butterfield and Johnston in 1980, Eggestad and Foyin in 1983, Lo et al. in 1991, Burnotte et al. in 2004, and also KhairulNizar (2012) and KhairulNizar and Clarke (2013).

The objectives of this paper are to demonstrate the implementation of electro osmotic process in small laboratory scale, plus to synthesize the effect of void ratio and the coefficient of volume compressibility due to electro osmotic process. The electro osmotic consolidation cell was designed and carried out in the laboratory with 345 mm height and 251 mm inner diameter.

## Methodology

The soil used in this study is China Clay Grade E kaolin. Kaolin was used due to its low in hydraulic permeability where it has a capability to be treated by electro osmotic consolidation treatment; and it also possesses the uniform repeatability. The complete sample preparation can be found from a study conducted by KhairulNizar (2012). The chemical characteristics of the kaolin are given in Table 1.

**Table 1: Index tests of kaolin grade be used in the tests**

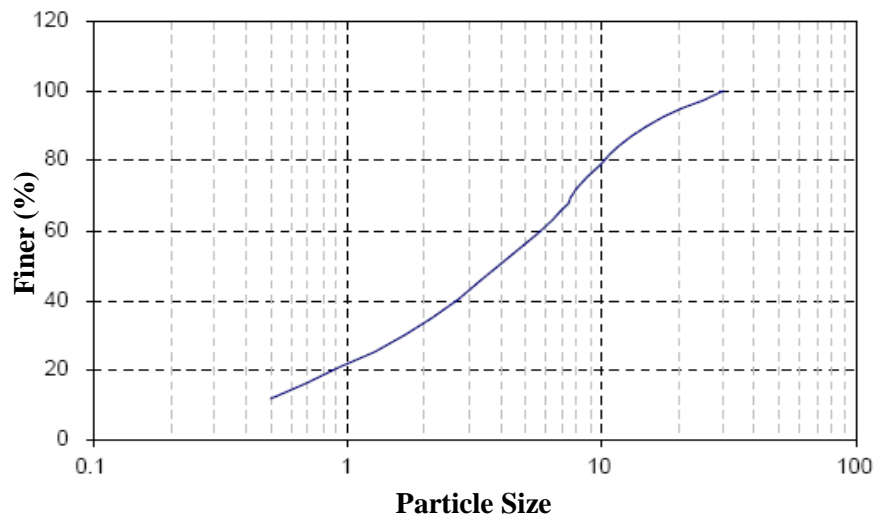
Soil Indexes	Hamir (1997)	KhairulNizar (2012)
Plastic Limit, $w_p$ (%)	34%	35%
Liquid Limit, $w_L$ (%)	55%	53%
Plasticity Index, $I_p$ (%)	20%	18%
Specific Gravity, $G_s$	2.60*	2.65*
Soil Classification	MH	MH

\*obtained from manufacturer's documentation.

## Soil Classification Test

The plastic and liquid limits were determined using the method described in BS 1377 in Part 2 in 1990 under Clauses 4.3 and 5.3 for liquid limits with cone penetrometer, and plastic limits, respectively. The particle size distribution was obtained from the information provided by the supplier which can be observed in

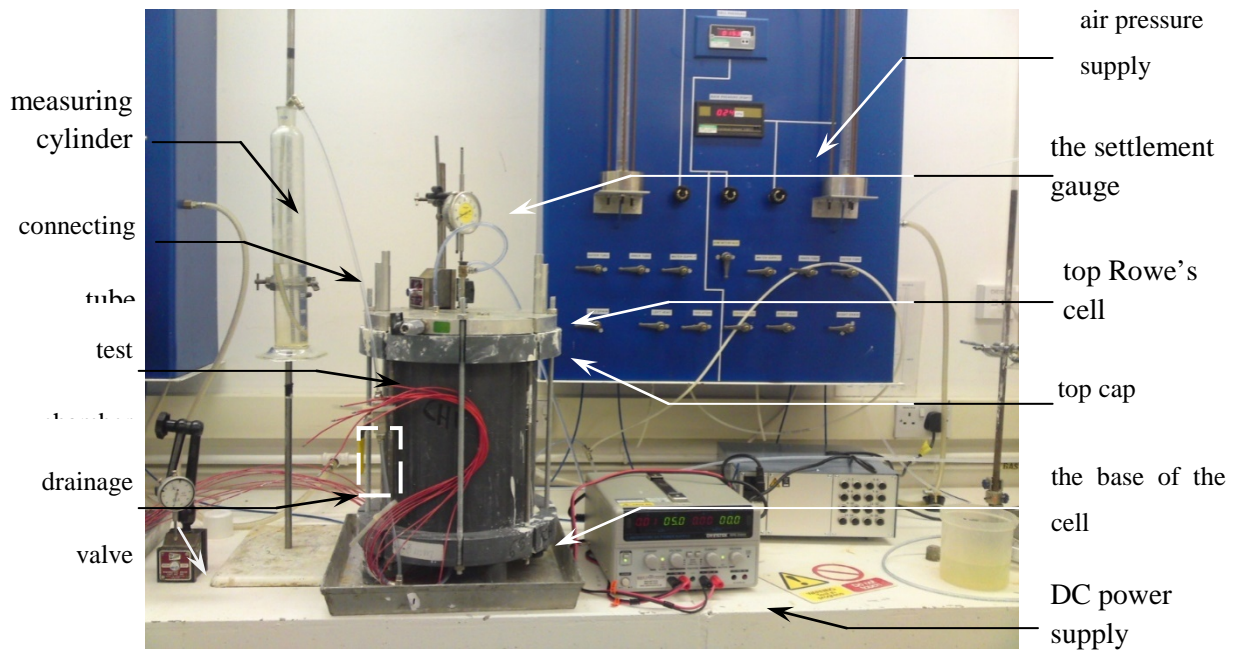
Figure 1 below. The kaolin used throughout the laboratory work was classified as well graded very fine clay (British Standard 1377-2:1990).



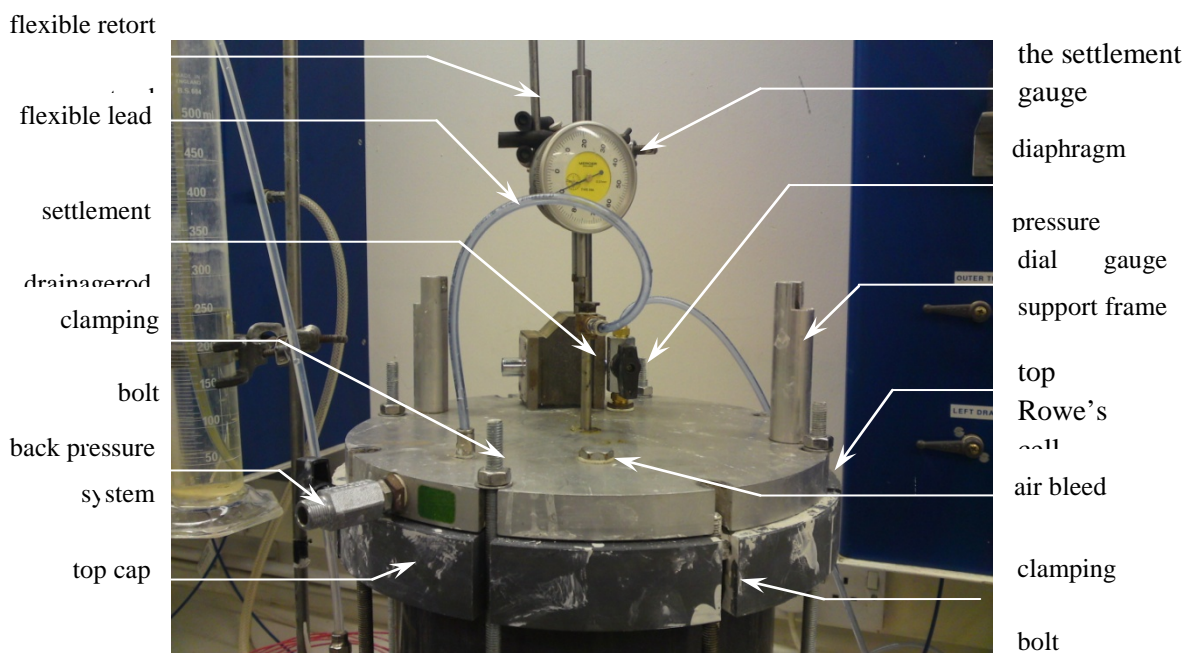
**Figure 1: Particle size distribution graph for grade E kaolin**

### **The Electro Osmotic Consolidation Chamber and its Loading Stages**

Figure 2 shows the general assembly of the electro osmotic consolidation chamber and the ancillary equipment. It also shows a section through the consolidation chamber. Figure 3 shows details of the control and measuring systems on top of the cell. The measuring cylinder and the settlement gauge were used to monitor the volume change of the sample. The control systems were the direct current power supply and air pressure supply. Pressure was applied to the top of the sample using a modified Rowe's cell pressure system.



**Figure 2: General arrangement of the electro osmotic consolidation chamber**



**Figure 3: Dial gauge and other parts**

Kaolin sample was undergoing a three-phase load. Loading phases are namely (i) Phase 1: sample was loaded with vertical load of 15 kPa (ii) Phase 2: the application of electro osmotic pressure, and finally the (iii) Phase 3: 50 kPa vertical load

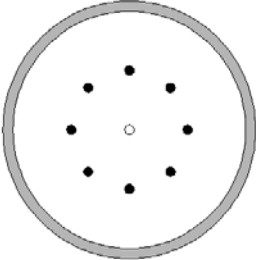
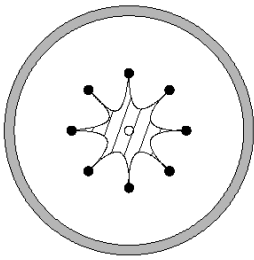
applications. In each phase the settlement of the top plate and the volume of water expelled were recorded. Since this was a consolidation test, readings were taken at a frequency used in standard consolidation tests, i.e, 0.167 min, 0.25 min, 0.5 min, 1 min, 2 mins, 4 mins, 8 mins, 15 mins, 30 mins, 60 mins, 120 mins, 240 mins, 480 mins, 1440 mins, 1680 mins, 1920 mins, 2880 mins, 4320 mins, 5760 mins, ... and 10080 mins. Phases 1 and 3 were terminated when primary consolidation had ceased. This was when no further water was expelled. The length of time for osmotic consolidation was one of the variables investigated.

## Results and Discussions

Configuration Q3 with 5 Volts for 24 hours of osmotic treatment was chosen (Table 2). The results of the vertical displacement versus time curves, and water expelled versus time curves are shown in Figures 4 to 13. These figures show that phase 1 and phase 3 required almost 14 days to reach the secondary compression phase. A total of 31.94 mm and 1613 ml of vertical displacement and water expelled readings occurred during Phase 1. Phase 1 and Phase 3 were carried out to avoid cracking and to measure average constrained stiffness, respectively.

A total of 847 ml water has been drained out and 17.47 mm of vertical displacement took place in Phase 3. In Phase 2, where the voltage was applied to treat the sample for 24 hours, it shows 24 ml water expelled and 0.49 mm of vertical readings, due to electro osmosis.

**Table 2: Electrode layout**

Electrodes Layout	Coded	Approximate of effective treated area	Polygon Type
	Q3		Concave octagon



o: positive terminal/anode; ●: negative terminal/cathode; : assumption of approximate of effective area; : assumption of approximate of ineffective area.

Figure 10 shows the volume calculated from the volume readings plotted against the volume of water expelled. The experimental line is very nearly at 45° which suggests the accuracy of the measurements was acceptable.

Figure 11 displays the water expelled and current readings versus time for Phase 2. The water expelled lines show that there was a gradual rise from the start of the experiment. During treatment the applied voltage and current were monitored continuously. The applied voltage was 5 Volts, and it remained constant over the test. The electric field within the electro osmotic consolidation chamber was generated by nine copper coiled spring electrodes. The output current was observed with time and the result is presented in Figure 11, showing that the current dropped gradually throughout treatment from 68 mA to 26 mA. The most noticeable difference between 2 hours and 8 hours is the increase in current with time where this is attributed to the increase in electrical conductivity of the soil pore fluid. The current decreases sharply in the last 16 hours from 63 mA to 37 mA as the corrosion process of the anode starts. The decrease of current with time under a constant voltage is attributed to the conduction and polarisation behaviour in such systems is dominated by ions.

The effect of electro osmotic consolidation treatment can be further evaluated from the water content after treatment. Figure 11 presents the results, where the determination of water content was only carried out on the surface near to the top internal plate. Micic et al. (2003) concluded that the water content at different depth was fairly uniform. Hence measurements of water content were only made at the surface. The initial water content was 79.5%. The water content at the end of the experiment was, on average 51.0%.

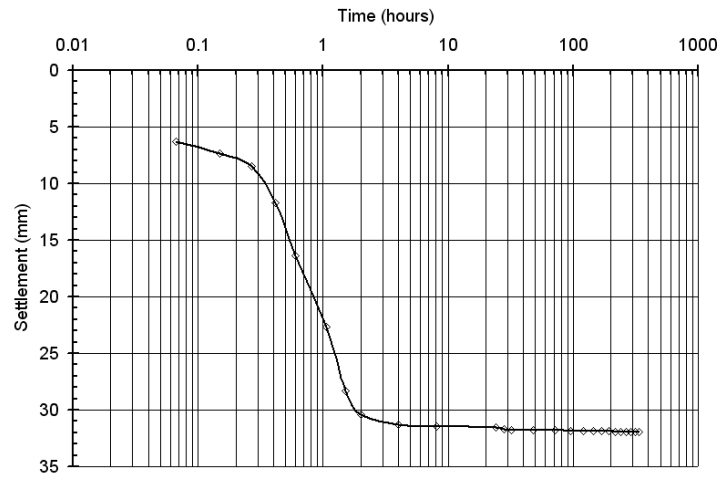
The voids ratio decreased from 2.123 at 0 kPa to 1.598 at 50 kPa. And at the end of Phase 3, the voids ratio shows that the value of the treated soil is slightly higher than that from the control test. Voids ratio changes in the control test are 0.200 at the end of 50 kPa compared to 0.182 for treated sample (Table 3 and Figure 13).

**Table 3: Summary of experiments after electro osmosis for Q3 sample treated with 5 Volts for 24 hours**

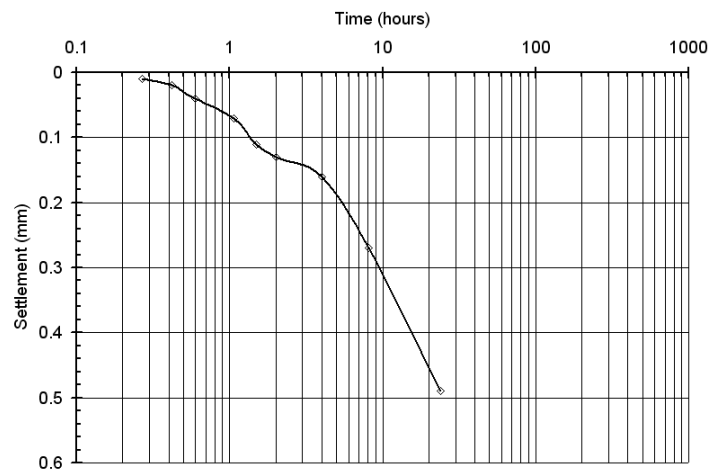
$\sigma'$ (kPa)	$\Delta H$ (mm)	$e_o$	$\Delta e_o$	$1 + e_{average}$	$\Delta e/\Delta \sigma'$	$m_v$ (m <sup>2</sup> /MN)
<b>0</b>	0	2.123	not applicable	2.956	0.022	0.0075
<b>15</b>	31.94	1.790	0.332			
<b>15 + 5 Volts</b>	1.02	1.780	0.011	2.689	0.005	0.0019

50	17.46	1.598	0.182			
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$\sigma'$ : pressure;  $\Delta H$ : vertical displacement;  $e_o$ : voids ratio;  $\Delta e_o$ : voids ratio change;  $e_{average}$ : average of voids ratio;  $m_v$ : the coefficient of volume compressibility.

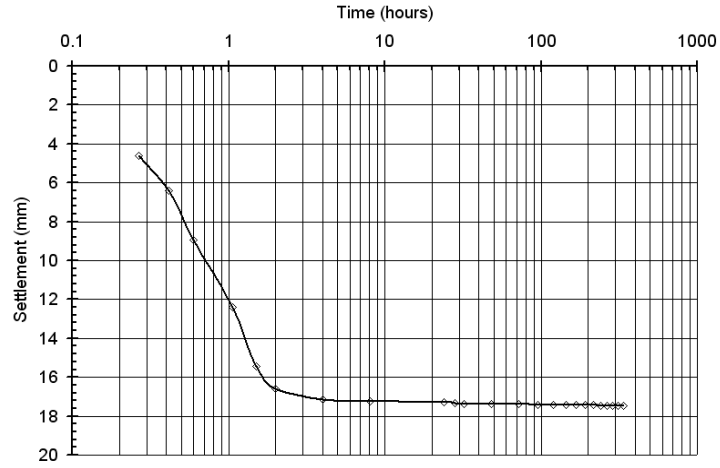


**Figure 4: Results for Q3 on phase 1: vertical displacement versus time**

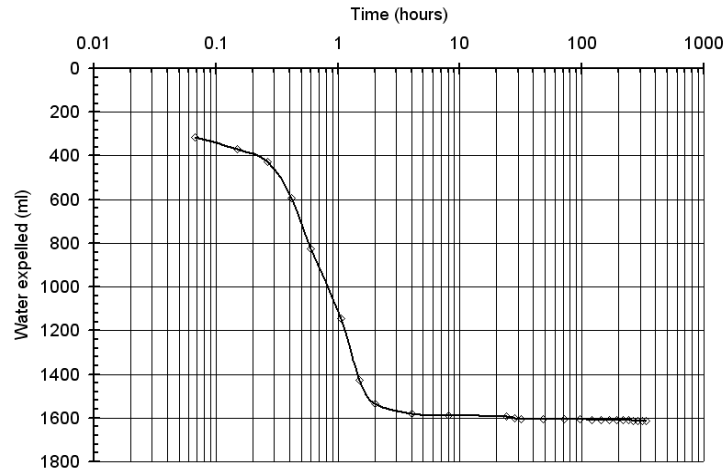


**Figure 5: Results for Q3 on phase 2: vertical displacement versus time**

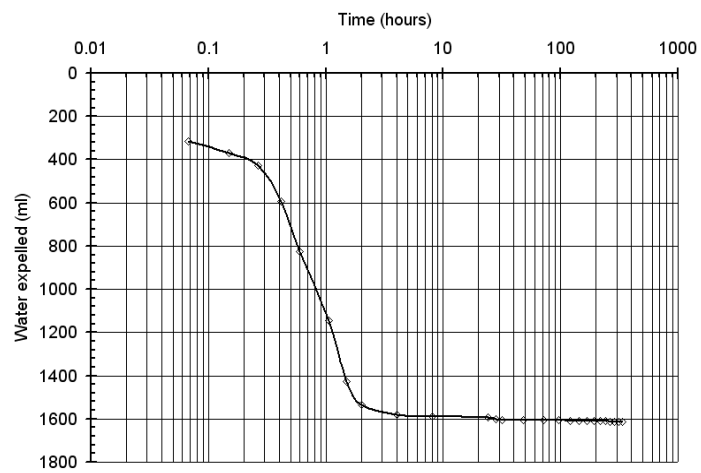




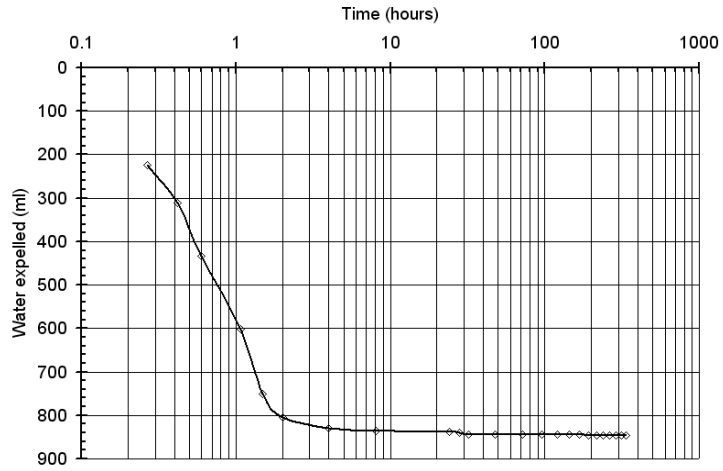
**Figure 6: Results for Q3 on phase 3: vertical displacement versus time**



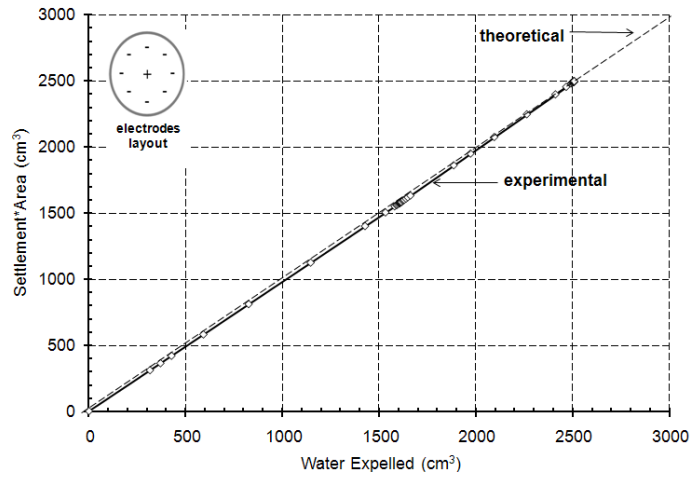
**Figure 7: Results for Q3 on phase 1: water expelled versus time**



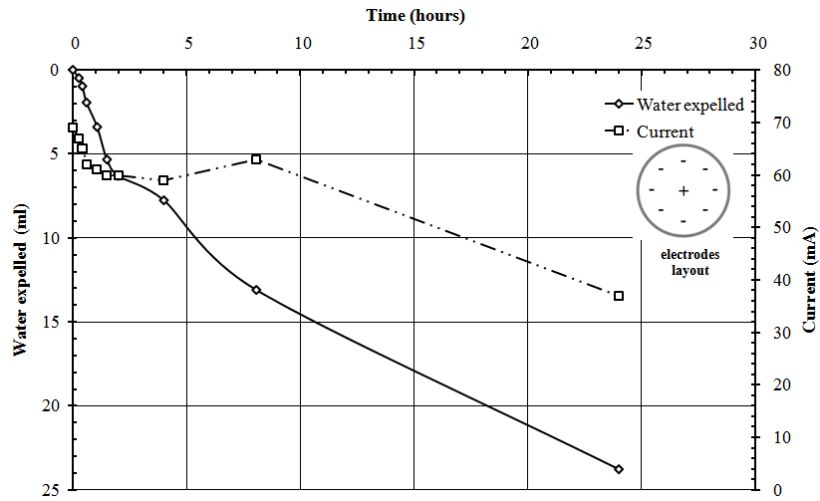
**Figure 8: Results for Q3 on phase 2: water expelled versus time**



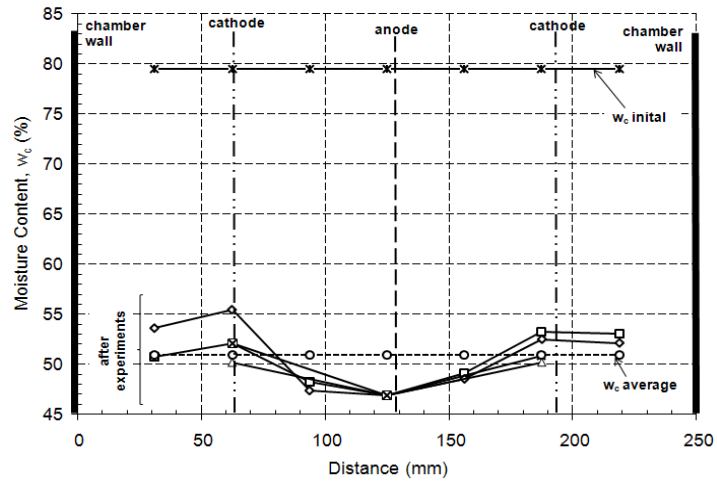
**Figure 9: Results for Q3 on phase 3: water expelled versus time**



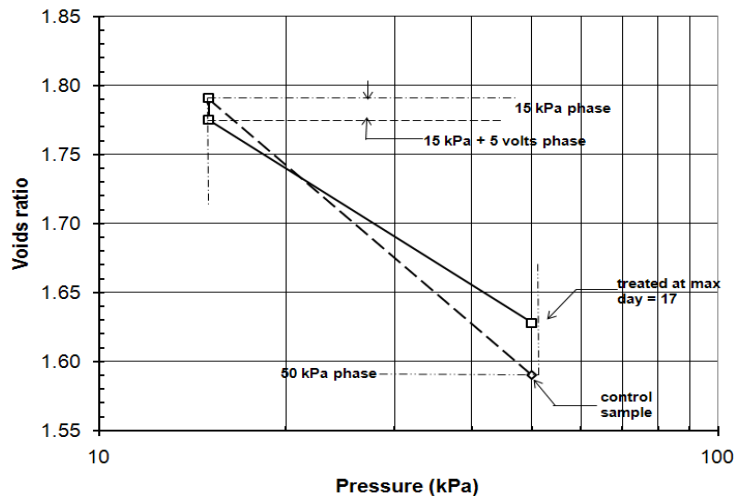
**Figure 10: Results for Q3: vertical displacement\*area versus water expelled**



**Figure 11: Results of Q3V51d test: water expelled and current versus time**



**Figure 12: Results of Q3V51d test: water content versus distance**



**Figure 13: Voids ratio for Q3V5 and control sample**

## Conclusion

The electro-osmotic consolidation treatment of kaolin slurry with 79.5% water content using one unit of anode and eight units of cathodes for 24 hours of applied voltage is an effective method. Significant stiffening effect at the end of vertical load application shows that this method has potential applications of improving soft soils in situ.

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