Electro-osmotic consolidation of soft Bangkok clay with prefabricated vertical drains

D. T. BERGADO,* A. S. BALASUBRAMANIAM,* M. A. B. PATAWARAN* and W. KWUNPREUK†

*School of Civil Engineering, Asian Institute of Technology, Bangkok, Thailand;
†Mahanakorn University of Technology, Bangkok, Thailand*

The response of reconstituted soft Bangkok clay to electro-osmotic consolidation was investigated using the small cylinder electro-osmotic cell and the large consolidometer. Test results indicated that employing electro-osmosis to induce consolidation produced a 3 to 4·4 times faster rate of consolidation. An 11·6–58% increase in shear strength with the reduction of water content was achieved for treated samples. In contrast, only 9·8–19·5% increase in shear strength was achieved without treatment. It was found that the 120 V/m voltage gradient and the 24 h duration of polarity reversal interval had maximum effect on the shear strength distributions and settlements between the electrodes.

Keywords: Consolidation; electro-osmosis; prefabricated vertical drains

Nous avons étudié la réponse d'une argile tendre reconstituée de Bangkok à la consolidation électro-osmotique en utilisant la petite cellule électro-osmotique cylindrique et le grand consolidomètre. Les résultats des essais montrent que l'emploi de l'électro-osmose comme moyen de consolidation produit une consolidation de 3 à 4,4 fois plus rapide. Pour les échantillons traités, nous avons obtenu une augmentation de 11,6 à 58% de la résistance au cisaillement avec la réduction du contenu en eau. A l'inverse, sans traitement, nous n'avons obtenu que 9,8 à 19,5% d'augmentation de la résistance au cisaillement. Nous avons trouvé que le gradient de tension de 120 V/m et l'intervalle de 24 heures pour l'inversion de polarité avaient un effet maximum sur les distributions de résistance au cisaillement et les tassements entre les électrodes.

Introduction

The generalized soil profile in Bangkok is relatively uniform, consisting of a 2 m thick weathered crust overlying approximately 6 m of very soft to soft Bangkok clay, which is in turn underlain by a 4 m thick medium clay and, thereafter, alternating layers of stiff clay and dense sand. Soft clay deposits are highly compressible and have low strength. When subjected to loading, they will consolidate and will undergo significant settlement which can have detrimental effects on structures. Due to the low permeability of clay primary consolidation takes longer to achieve. The use of pre-loading with sand surcharge and prefabricated vertical drains (PVDs) hastens consolidation. However, the consolidation period can be further precipitated by electro-osmosis. Electro-osmosis is the process whereby positively charged ions move from anode to cathode carrying hydrated water with them upon the application of direct current. Consolidation results when water is drained at the cathode but not replaced at the anode. It has been proven to be effective in stabilizing and consolidating soils both in the laboratory and in the field. Results indicated the reduction of moisture content and increase in shear strength. This process can also be used in remediation of contaminated soils and groundwater.

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Electro-osmotic consolidation

Electro-osmosis (EO) is the process whereby positively charged free water moves from the anode to the cathode upon application of a direct current. In a clay–water system, the double layer of water consists of a fixed part and a diffused part. Water, which is dipolar, is attracted both by the negatively charged surface of the clay particles and by the cations in the double layer. If a direct current is applied to a system, cations in the diffuse double layer move towards the cathode to gain electrons and thereby become discharged. As the cations move, they carry with them water so that there is a new movement of water towards the cathode. During the process, pore water pressure changes develop in the soil mass. Assuming that the total stress remains constant, the changes in pore water pressure therefore will bring about changes in the effective stress of the soil and, eventually, changes in the soil strength. Consolidation will then result if water is removed at the cathode but not replaced at the anode.

According to Esrig (1968), the electrically induced velocity of water flow through the soil, $\boldsymbol{v}_e$, and the voltage gradient (electric field) $\partial V/\partial x$, are related by the proportionality factor, k_e, called the coefficient of electrokinetic permeability, and is given by

$$\boldsymbol{v}_e = k_e \frac{\partial V}{\partial x} \quad (1)$$

By Darcy's law (Esrig, 1968), the velocity of flow, $\boldsymbol{v}_h$, due to any excess pore water pressure gradient is given by

$$\boldsymbol{v}_{\mathrm{h}} = \frac{k_{\mathrm{h}}}{\gamma_{\mathrm{w}}} \cdot \frac{\partial \boldsymbol{u}}{\partial x} \tag{2}$$

in which k_h is the hydraulic permeability, $\boldsymbol{u}$ is the excess pore water pressure, and γ_w is the unit weight of water.

By assuming the validity of superposing electrically and hydraulically induced flows, it follows that

$$\frac{\partial \boldsymbol{v}_{\mathrm{e}}}{\partial x} + \frac{\partial \boldsymbol{v}_{\mathrm{h}}}{\partial x} = 0 \tag{3}$$

Differentiating the term yields

$$k_{\mathrm{e}} \frac{\partial^2 V}{\partial x^2} + \frac{k_{\mathrm{h}}}{\gamma_{\mathrm{w}}} \frac{\partial^2 \boldsymbol{u}}{\partial x^2} = 0 \tag{4}$$

Under a uniform voltage gradient (Esrig, 1968), developed pore pressures are dependent on the boundary conditions. For an anode closed and cathode open with free access to water condition, $\boldsymbol{u}$ is given by

$$\boldsymbol{u} = -\frac{k_{\mathrm{e}} \cdot \gamma_{\mathrm{w}}}{k_{\mathrm{h}}} V \tag{5}$$

where V is the voltage. Therefore, a closed anode produces negative pore water pressures at any point that is proportional to the voltage. Nettleton *et al*. (1998), on experiments with electrically conductive geosynthetics (ECGs), generated negative pore pressures during EO. Upon the application of current, the pore pressures measured at the anode decreased to a value lower than the back pressure, signifying negative pore pressures.

The electrolysis reactions at the electrodes caused by the application of the electric current generate an acid front at the anode and a basic front at the cathode. The reaction equations at the anode and cathode can be expressed, respectively, as (Acar *et al*., 1994)

$$2H_2O - 4e^- \rightarrow O_2\uparrow + 4H^+ \tag{6}$$

$$4H_2O + 4e^- \rightarrow 2H_2\uparrow + 4OH^- \tag{7}$$

Polarity reversal is an effective technique in preventing excessive desiccation at the anode and decreasing electrode corrosion. It promotes a more uniform water content and shear strength distribution due to a more uniform increase in the effective stress and improved development of pore pressure (Gray and Somogyi, 1977; Shang *et al*., 1996).

Previous studies on soft Bangkok clay

A study was conducted by Nayar (1997) to evaluate the improvement of compressibility and strength of soft Bangkok clay with electro-osmotic stabilization with or without PVDs and to determine the coefficient of electro-osmotic permeability using a Rowe cell with some modification to suit the drain size requirements. The brass body of the Rowe cell and a strip of copper wire wound around the core of the drain were used as electrodes. Investigation was conducted on different types of drain at different effective stresses, different voltage gradients and different polarity reversal durations. It was found that the horizontal coefficient of consolidation increased with the decrease in vertical stress and increase in applied voltage gradient. Test results also showed an increase in shear strength after the consolidation.

Chaudhary (1998) has undertaken a comprehensive investigation into the electro-osmotic stabilization of soft Bangkok clay using modified triaxial and oedometer cells which allow measurement of settlement and pore pressure at the anode. Porous and non-porous copper discs were used as cathode (bottom) and anode (top), respectively, instead of the usual porous stones. The cutting ring and the ring retainer used in the oedometer cells were made of plexiglass and the reservoir was only half-filled with distilled water to avoid short-circuiting during electro-osmosis. The consolidation characteristics, the change in moisture content and strength of soil, the change in current and voltage with time, the effect of chemical hardening, the negative pressure developed and the effect of polarity reversal were evaluated to examine the effectiveness of the process. Test results show that the magnitude of settlement, negative pore water pressure at the anode, and shear strength increase with voltage gradient. It was also observed that water content reduction is at maximum near the anode and at minimum near the cathode, but that polarity reversal can reduce this non-uniformity.

Patawaran (1998) performed an experiment to evaluate the effects of PVD improvement on reconstituted soft clay with or without electro-osmosis using a large-scale consolidation test apparatus. The loading piston has four shafts arranged in a square pattern, 200 mm apart in the centres, to facilitate PVD installation of Castle Board drains 20 mm wide with a spacing of 200 mm to simulate the field condition of 100 mm drains placed 1 m apart. A load of 50 kPa was used to reconstitute the sample. After 90% consolidation was achieved, the drains were inserted with the aid of a mandrel and the load was increased to 75 kPa. A voltage ratio of 80 V/m was used, performing polarity reversal every 48 h. Using the same voltage ratio, the load was increased to 82·5 kPa to check the effect of surcharge. Under the influence of EO consolidation, a 10% increase in the surcharge load generated a reduction in the water content of the soil which was three times as much as that under the lower load. Shear strength increase was noticed at the anode after the application of EO.

Experimental investigation

Dinoy (1999), under the supervision of the first author, performed electro-osmosis experiments using both small cylinders and the large consolidometer. Soil samples from 3–4 m depth were obtained from the Asian Institute of Technology campus. Index properties such as water content and Atterberg limits were determined before and after electro-osmotic consolidation. Two types of apparatus were utilized: four small cylinders and a large consolidometer. A reconstituted sample—soil mixed thoroughly with a substantial amount of distilled water—was placed inside the apparatus in layers.

The set-up of the small cylinder apparatus is shown in Fig. 1. This apparatus is similar to the one used by Abiera *et al*. (1998). Vertical load application on the top cap is through a loading piston where air pressure is being supplied by a compressor and is controlled by a valve regulator. The electro-osmotic cell can accommodate a disturbed sample up to a height of 300 mm and an inner diameter of 300 mm. Two holes at the top and bottom cap are provided for PVD installation. Geotextile filters were provided between the soil sample and the caps. Dial gauges were provided to monitor settlement during the reconstitution and electro-osmosis consolidation process. Light was prevented from entering the soil sample to prevent the development of moulds in the sample. The PVDs with electrodes were connected to a power supply with a switchbox for current measurements.

Four small cylinders were used in the test under recon-

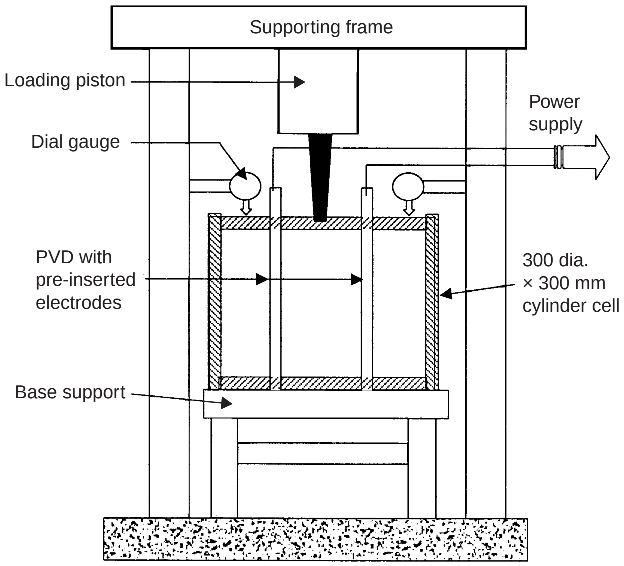

Fig. 1. Experimental set-up of the small cylinder electro-osmotic cell

stitution pressures of 5 kPa. After reconstitution, the drains were installed and the overburden pressures were maintained at 5 kPa until 90% consolidation was attained. The samples were designated as 1A5, 1B5, 1C5 and 1D5. Test 1A5 was conducted under normal conditions without electro-osmotic consolidation. Tests 1B5 and 1C5 underwent electro-osmotic consolidation at 60 V/m voltage gradient as well as at 12 h and 24 h polarity reversal durations, respectively. Test 1D5 underwent electro-osmotic consolidation at 120 V/m voltage gradient and at 24 h polarity reversal interval.

The large consolidometer was used to determine the rate of electro-osmotic consolidation considering the effects of variable voltage gradient and polarity reversal duration. Silicon grease was applied to the insides of the cylinder to reduce friction. A schematic diagram of the apparatus, which was previously used by Patawaran (1998), is shown in Fig. 2. It is made up of 10 mm diameter thick transparent PVC sheet 950 mm high, with an internal diameter of 450 mm, placed over a steel base plate. Load is applied through a special regulator valve. The loading piston has four shafts arranged in a square pattern and 200 mm apart in the centres to facilitate PVD installation. Dial gauges were placed on top of these shafts for settlement measurement. A lid placed on top of the PVC tube and tightened by eight screws holds the apparatus in place. Steel rings are wrapped around the cylinder to prevent bulging. Mebra drains of 20 mm width, with a spacing of 200 mm to simulate the field condition of 10 mm drains placed 1 m apart, were used. A 30 mm mandrel was used to aid the installation of the PVDs. Geotextile was placed on top of the soil to prevent clogging of the loading piston. Six rubber balloons were arranged on top of the loading piston to ensure uniform loading. A load of 50 kPa was used to reconstitute the sample. The experimental set-up of the small electro-osmotic cylinder and the large consolidometer are shown in Figs 3 and 4 respectively.

Four tests were performed in this series in a single set-up. The reconstitution pressure applied was 50 kPa. After reconstitution, the drains were installed and the pressure was increased to 75 kPa, allowing the sample to consolidate without electro-osmotic consolidation for eight days. Electro-osmotic consolidation commenced with the application of 80 V/m voltage gradient at a 24 h polarity reversal interval. The polarity reversal interval was then increased to 48 h and its effect was noted. Finally, the voltage gradient was

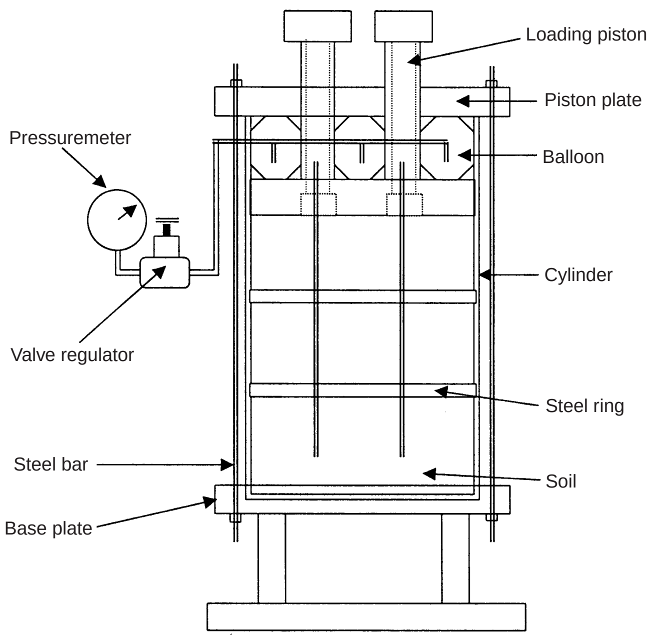

Fig. 2. Schematic diagram of the modified large consolidometer (Patawaran, 1998)

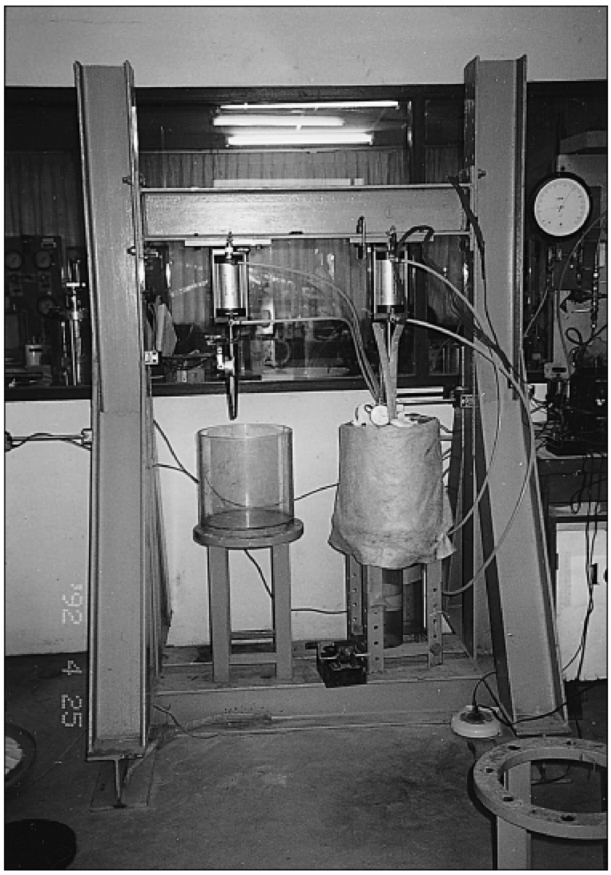

Fig. 3. Small electro-osmotic cylinder experimental set-up

Fig. 4. Large consolidometer experimental set-up

increased to 120 V/m under a 24 h polarity reversal interval. Each test duration was maintained for eight days.

Shear strength measurements were taken using the laboratory vane shear apparatus before and after electro-osmotic consolidation. Figs 5 and 6 show the measurement of shear strength of the specimen in the small electro-osmotic cylinder and the large consolidometer, respectively,

Fig. 5. Shear strength measurement using laboratory vane shear on the small electro-osmotic cylinder

Fig. 6. Shear strength measurement using laboratory vane shear on the large consolidometer

by using the laboratory vane apparatus. The test point locations of the laboratory vane are shown in Figs 7 and 8 for the small cylinder and the large consolidometer, respectively.

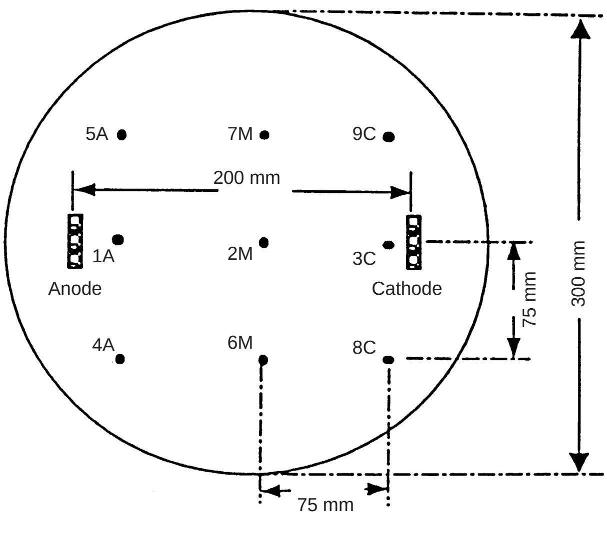

Fig. 7. Shear strength test location points for the small cylinder electro-osmotic cell

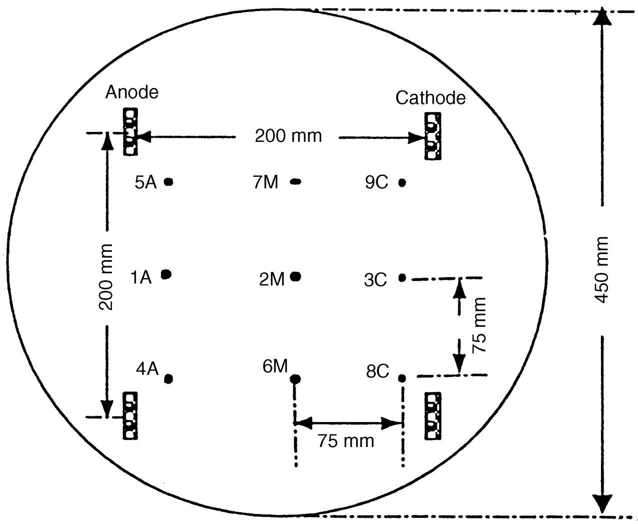

Fig. 8. Shear strength test location points for the large consolidometer

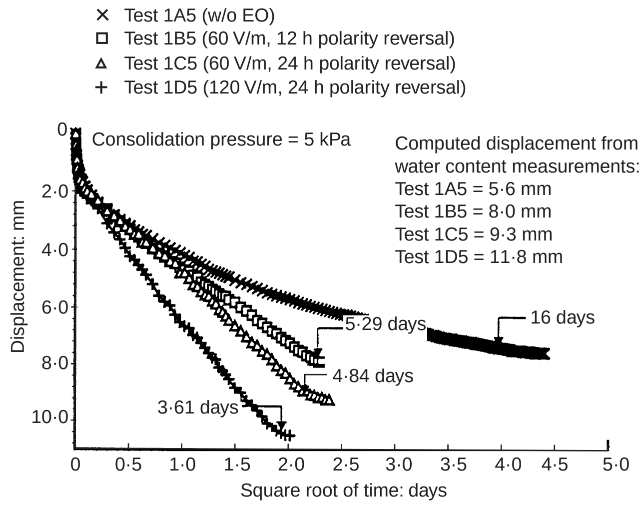

Fig. 9. Displacement plotted against the square root of time for the small cylinder apparatus with and without electro-osmotic consolidation

Test results

Small cylinder cell

The application of EO increased the rate of consolidation for reconstituted Bangkok clay as shown in Fig. 9. For the untreated sample (test 1A5), it took 16 days to achieve 90% consolidation with a settlement of 7·4 mm. Test 1B5 (60 V/m voltage gradient, 12 h polarity reversal duration), test 1C5 (60 V/m voltage gradient, 24 h polarity reversal duration), and test 1D5 (120 V/m voltage gradient, 24 h polarity reversal duration) had attained 90% consolidation within 5·3, 4·8 and 3·6 days, respectively. The settlement attained using electro-osmotic consolidation was 6–40% greater than the sample without electro-osmotic consolidation at the end of the test. A 4·4 times faster rate of consolidation was observed at the higher applied voltage gradient of 120 V/m and longer duration of 24 h polarity reversal. Generally, the settlement was slightly higher at the anode. However, the

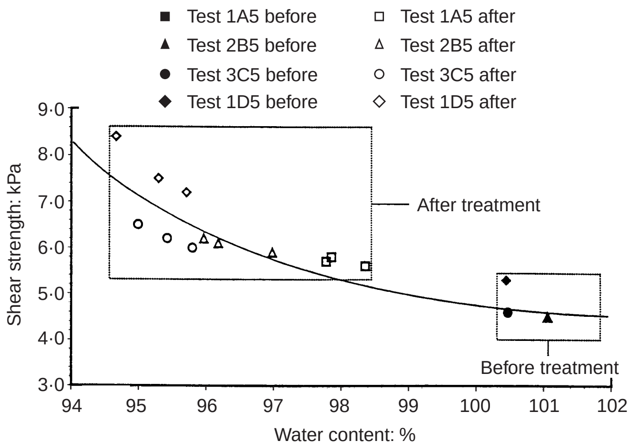

Fig. 10. Relationship between shear strength and water content of the small cylinder cell with electro-osmotic consolidation and PVDs

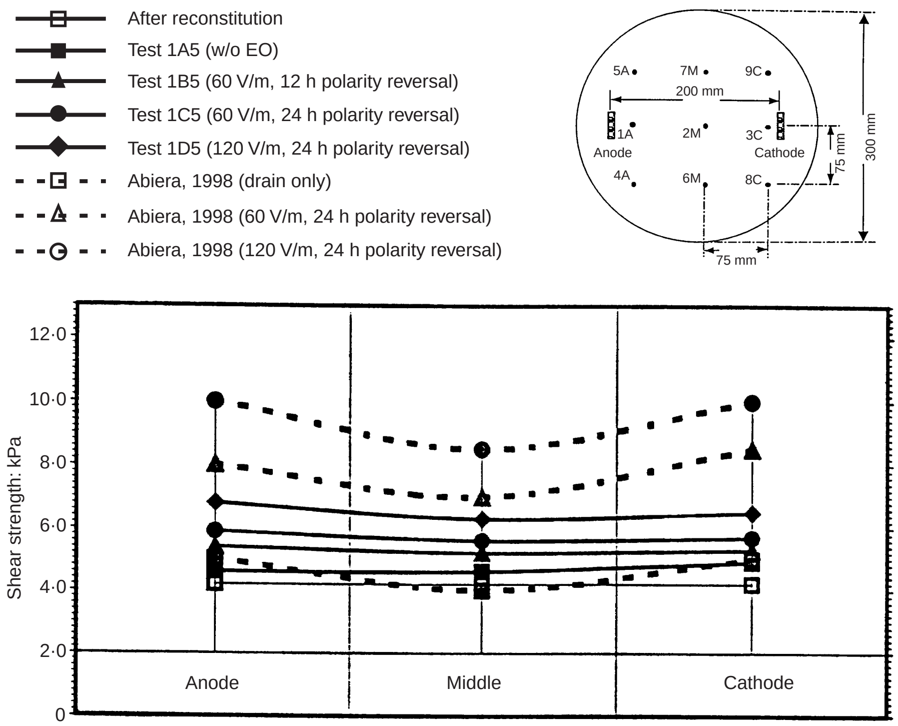

Fig. 11. Shear strength increase due to electro-osmotic consolidation with PVDs using small cylinder apparatus

differential settlement was smaller at shorter duration of polarity reversal.

Abiera *et al*. (1998) investigated the electro-osmotic dewatering effect using electro-conductive and non-electro-conductive drains in the consolidation of reconstituted Ariake clay in Japan. Using a similar apparatus, the settlements obtained were ~ 40–100% higher and the rate was two to three times faster in achieving 90% consolidation when using electro-conductive drains at 120 V/m and at overburden pressures of 2 and 4 kPa, respectively. As mentioned previously, the rate of electro-osmotic consolidation with PVDs for the reconstituted soft Bangkok clay was 4·4 times faster. This higher rate of consolidation can be attributed to higher applied overburden pressure. The results also showed a more uniform water content reduction and shear strength increase when polarity reversal was being implemented. Without the application of polarity reversal, excessive desiccation was evident at the vicinity of the anode, showing fissures up to 2 mm in width.

Figure 10 shows the relationship between water content and shear strength before and after treatment. For the samples treated with EO, there was a significant increase in strength observed of about 30% at the anode and 58·5% at the cathode. The samples not treated with EO showed an increase of only 9·8–19·5% in shear strength. The increases in shear strength due to electro-osmotic consolidation are

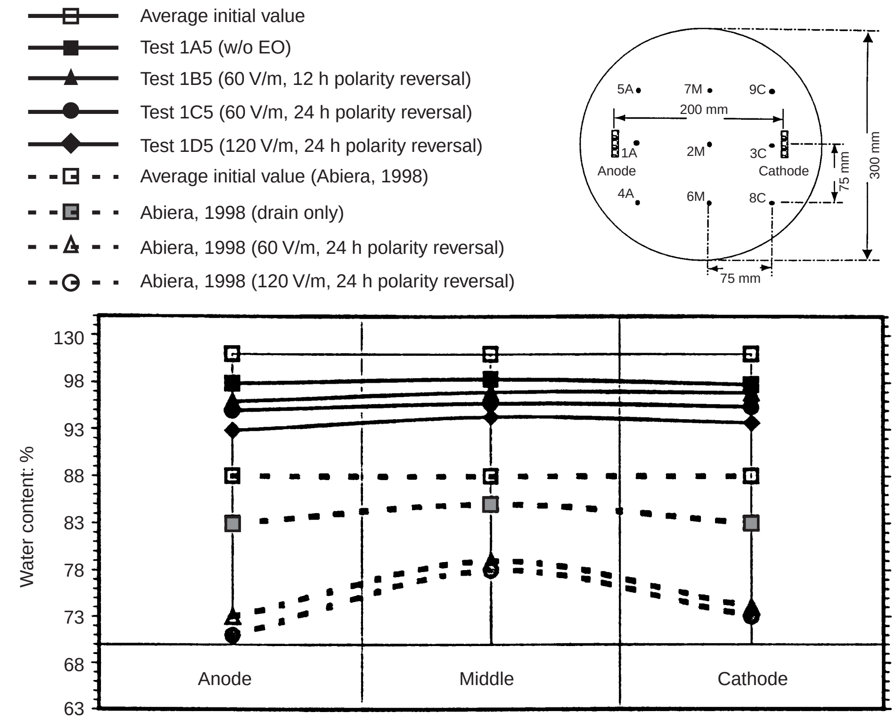

Fig. 12. Reduction of water content due to electro-osmotic consolidation with PVDs using small cylinder apparatus

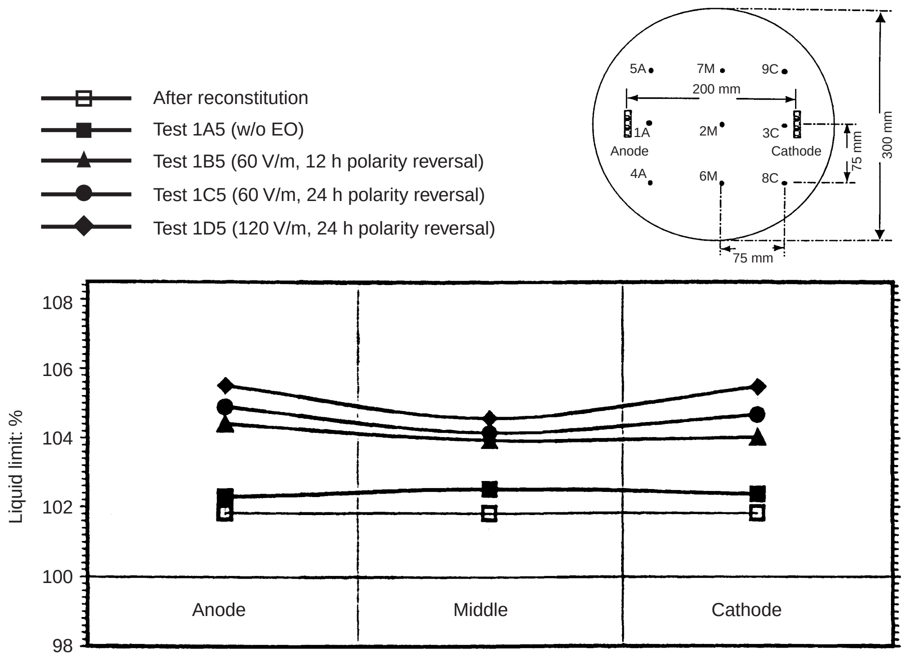

Fig. 13. Variation of liquid limit due to electro-osmotic consolidation with PVDs at different voltage gradients and polarity reversal durations of the small cylinder

shown in Fig. 11. In this figure, the results of Abiera *et al.* (1998) are also plotted for comparison. A greater increase in strength was also observed at higher electric potential gradients. Generally, a slightly larger increase was noticed at the anode, which was also observed by Abiera *et al.* (1998). The application of polarity reversal resulted in a symmetrical distribution of shear strength increase across the electrodes, especially in the sample subjected to a shorter polarity reversal duration.

There was a reduction of moisture content after the treatment, as shown in Fig. 12. Test 1A5 (without EO) reduced its water content to as low as 97·9% from the initial value of 100·95%, resulting in a 3·1% reduction by the time 90% degree of consolidation was achieved. The water

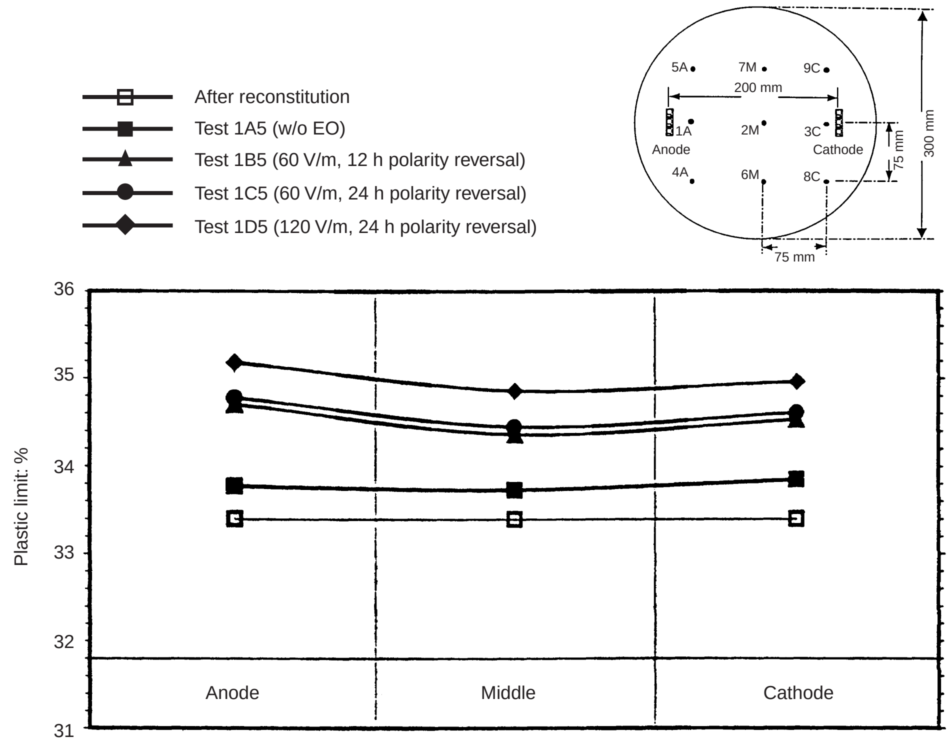

Fig. 14. Variation of plastic limit due to electro-osmotic consolidation with PVDs at different voltage gradients and polarity reversal durations of the small cylinder

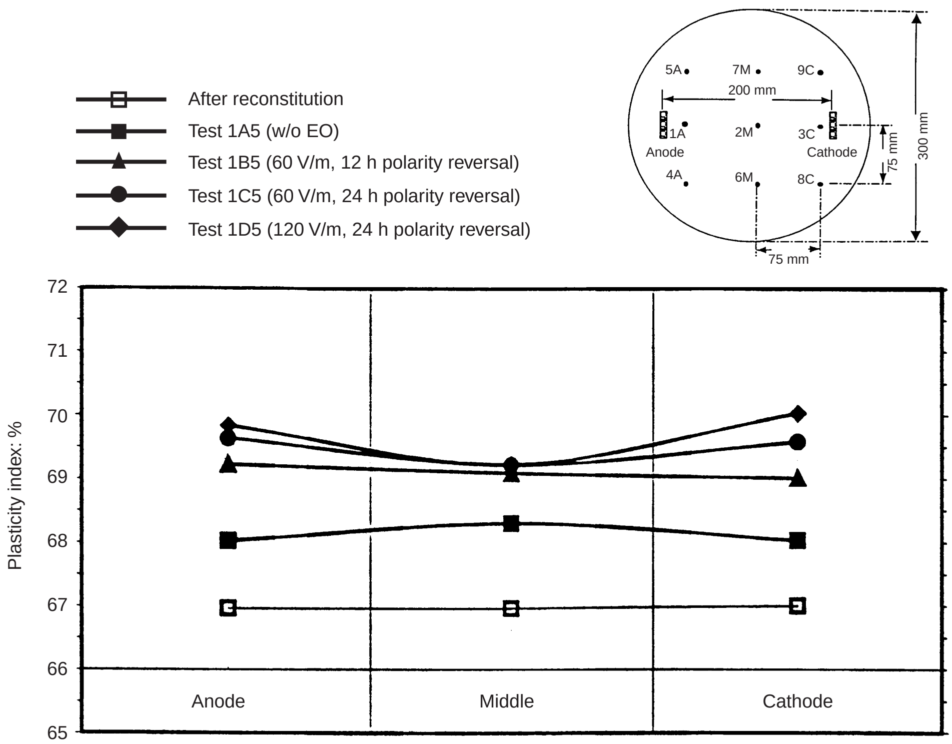

Fig. 15. Variation of plasticity index due to electro-osmotic consolidation with PVDs at different voltage gradients and polarity reversal durations of the small cylinder

content reduction with the application of EO is close to that of an untreated sample, being about 4·1–8·1%. However, the reduction of water content was achieved in a shorter time. Reduction of moisture content increased with increasing voltage gradient, a factor that was also observed by Abiera *et al*. (1998). Unlike the untreated sample where there was a more uniform distribution of water content across the drains, the maximum reduction in water content was observed around the vicinity of the anode and decreased around the cathode, since the movement of hydrated water, which is being carried by cations, is towards the cathodes. Nevertheless, a more even distribution of water content across the electrodes was observed with shorter duration of polarity reversal.

Figures 13–15 show the summary of the changes of the liquid limit, plastic limit, and plasticity index, respectively, caused by electro-osmotic consolidation with PVDs. Polarity reversal resulted in a fairly uniform distribution of liquid and plastic limits between electrodes. The initial values of the liquid limit and plastic limit were 98·4–101·4% and 33·1–33·7%, respectively. After the treatment, liquid limit and plastic limit, respectively, had an increase of 1·7–6·7% and 3·2–5·7%. Consequently, the plasticity index slightly increased from 34·5 to 35·2%. This increase in plasticity was observed by Abiera *et al*. (1998) to be due to the increased salt concentration caused by the electro-chemical reactions generated by EO. Ion exchange and diffusion, generation of pH gradients, and soil desiccation from heat generated during application of current are some of the factors contributing to permanent changes in the strength and plasticity characteristics of the clay.

Large consolidometer

The time–settlement plot of the whole test series using the large consolidometer apparatus is presented in Fig. 16. The first test of the series (i.e. test 2LA75) attained a settlement of 24 mm. A steeper slope of the settlement curve for the tests treated with EO indicated a faster rate of

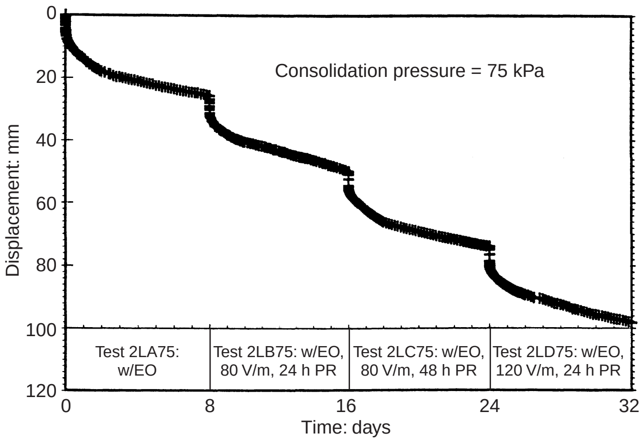

Fig. 16. Time–displacement plot at different voltage gradients and polarity reversal durations of the large consolidometer

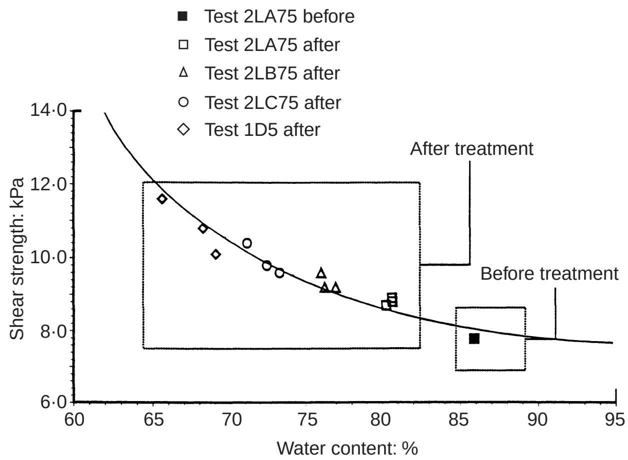

Fig. 18. Relationship between shear strength and water content of the large consolidometer due to electro-osmotic consolidation with PVDs

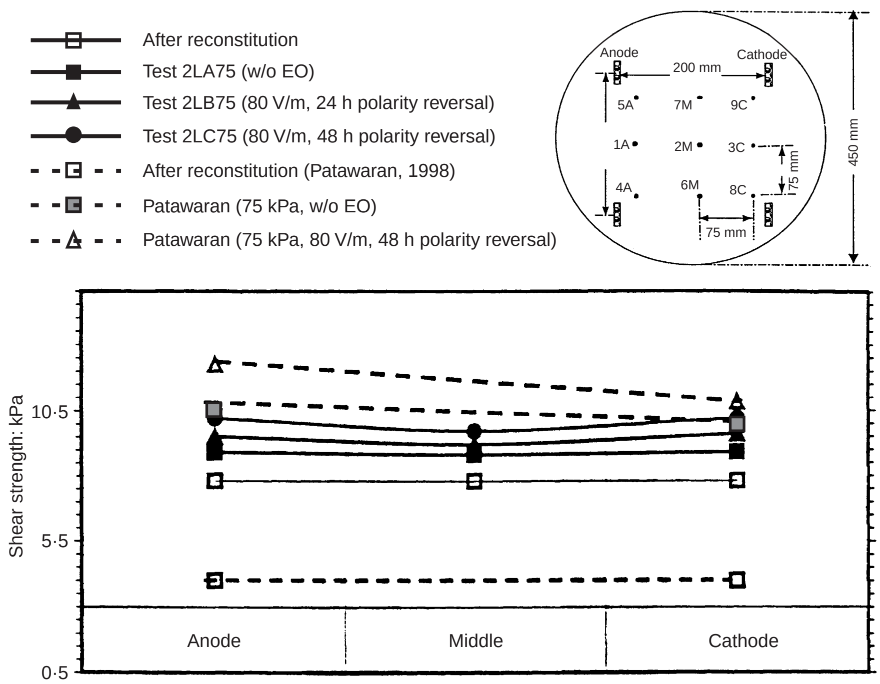

Fig. 17. Increase in shear strength at 75 kPa overburden pressure (80 V/m) using the large consolidometer apparatus due to electro-osmotic consolidation with PVDs

settlements. The magnitude of settlement, however, could not be the basis of comparison in the large consolidometer since the tests were done in series using the same clay specimen.

The shear strength increase was attained at different depths after the treatment. The shear strength profile/distribution is shown in Fig. 17 together with the previous results on shear strength done by Patawaran (1998). Generally, a larger increase in strength is at the vicinity of the anode. Fig. 18 shows the relationship between water content and shear strength before and after consolidation. The shear strength increased as water content decreased.

There was a reduction in moisture content after each test, as shown in Fig. 19. Test 2LA75 (without EO) reduced its water content to as low as 80·2% from the initial value of 85·9%, resulting in a 5·7% reduction for an eight-day testing duration. Further reduction was achieved upon the application of EO. A greater reduction in water content (7·8%) was attained for the test with higher voltage gradient (120 V/m) and constant polarity reversal duration (24 h). Maximum reduction was observed at the anode and minimum at the cathode. Patawaran (1998) observed a similar trend of results regarding the reduction of moisture content, as shown in Fig. 19.

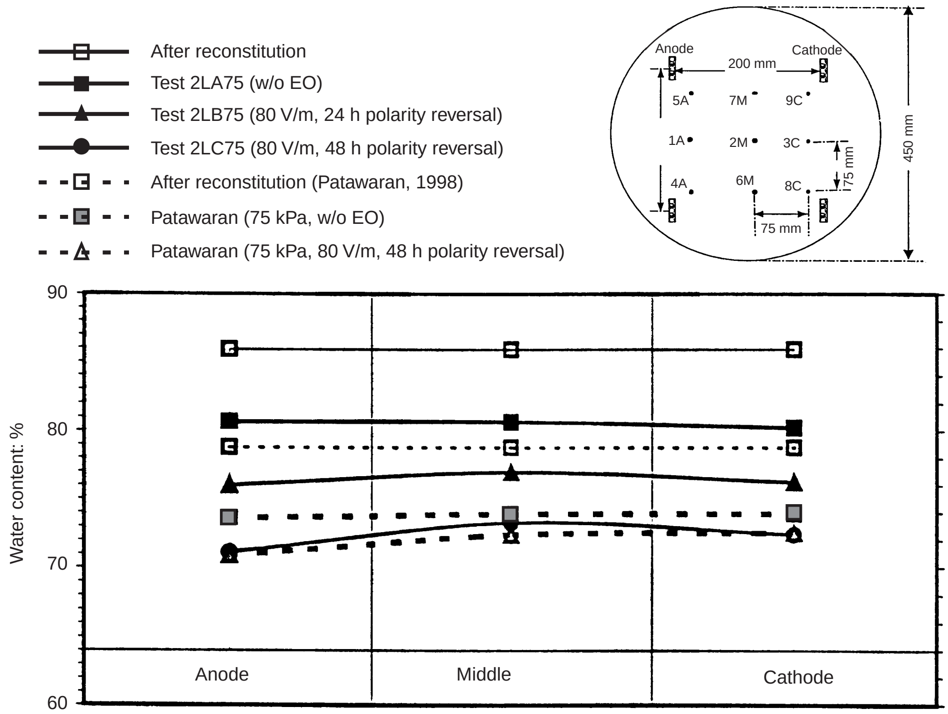

Fig. 19. Reduction of water content at 75 kPa overburden pressure (80 V/m) due to electro-osmotic consolidation with PVDs using the large consolidometer

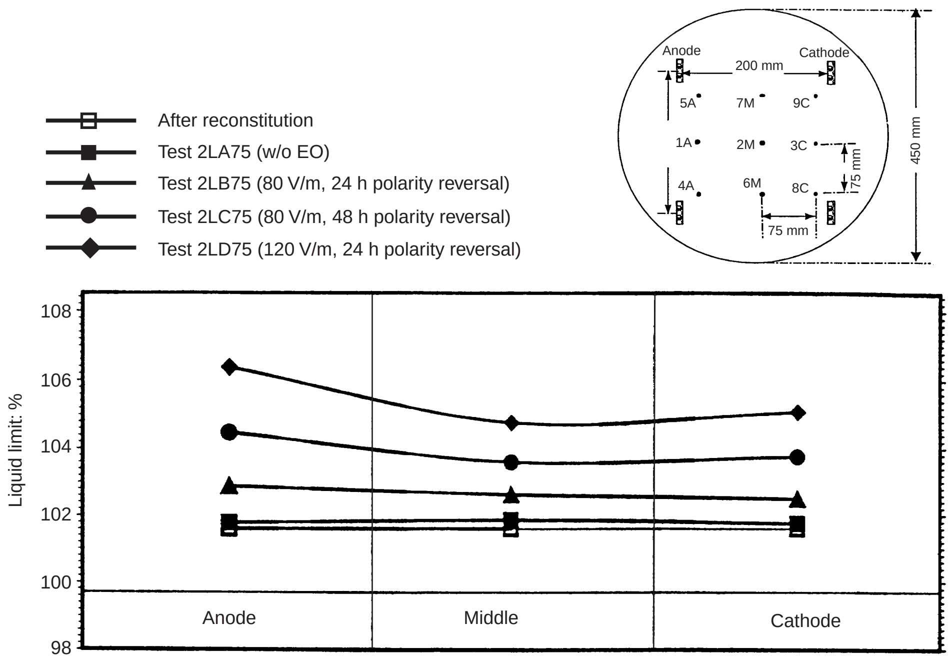

Fig. 20. Variation of liquid limit due to electro-osmotic consolidation with PVDs at different voltage gradients and polarity reversal durations of the large consolidometer

During the implementation of polarity reversal, a similar trend of results was obtained from the experiment using the small cylinder electro-osmotic cell. Polarity reversal resulted in a fairly uniform distribution of liquid and plastic limits between electrodes, especially observed at shorter duration, as shown in Figs 20 and 21, respectively. The initial values of the liquid limit and plastic limit were 101·1% and 33·8%, respectively. After the treatment, the liquid limit and plastic limit had increased by as much as 8·9% and 4·7% respectively. Consequently, upon the application of EO, there was

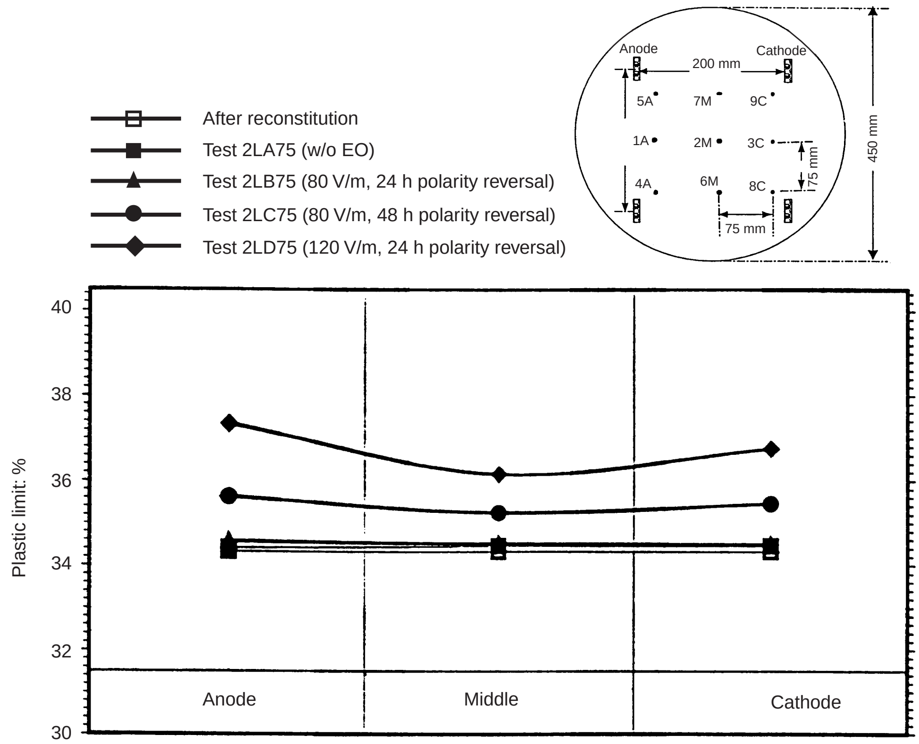

Fig. 21. Variation of plastic limit due to electro-osmotic consolidation with PVDs at different voltage gradients and polarity reversal durations of the large consolidometer

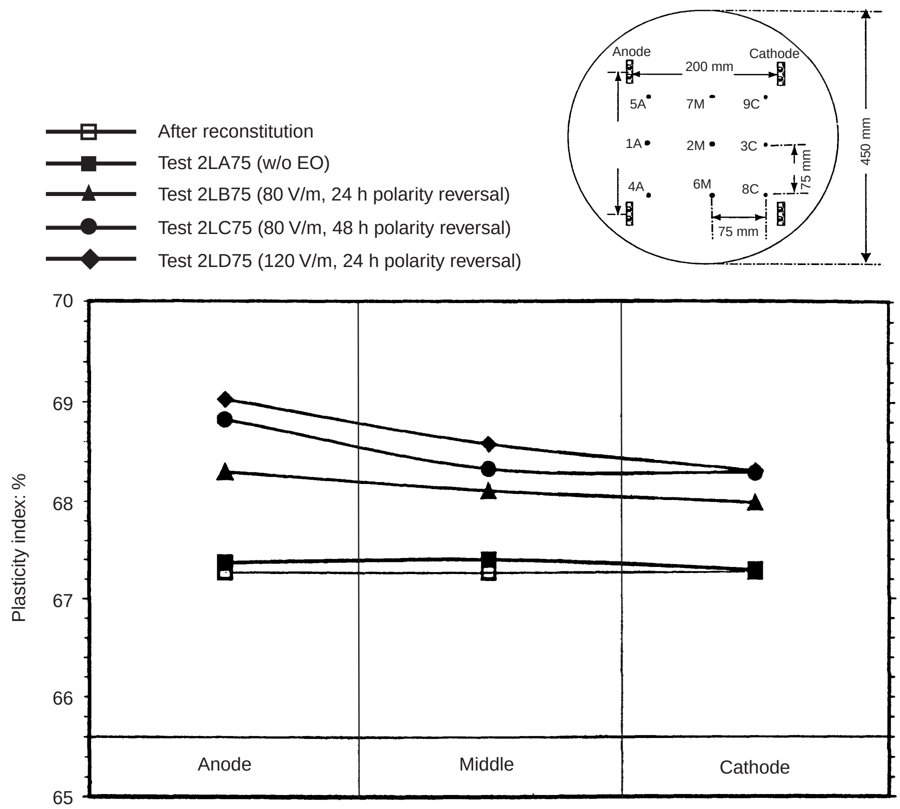

Fig. 22. Variation of plasticity index due to electro-osmotic consolidation with PVDs at different voltage gradients and polarity reversal durations of the large consolidometer

a slight increase in plasticity index in the sample from 67·3 to 69%. The variations in the plasticity index are shown in Fig. 22. The increase in liquid limit coupled with the slight increase in the plastic limit combined to bring about an increase in plasticity. This increase in the water-holding capacity of the clay can be attributed to the increase in its salinity. EO brought about electro-chemical changes in the soil fabric, resulting in higher strength and plasticity (Abiera *et al*., 1998).

Conclusions

From the results of the electro-osmotic consolidation with PVDs, the following conclusions can be drawn.

(*a*) The rate of electro-osmotic consolidation with PVDs was found to be 3–4·4 times faster compared to ordinary consolidation with PVDs. It took 5·3 days (60 V/m voltage gradient, 12 h polarity reversal duration), 4·8 days (60 V/m voltage gradient, 24 h polarity reversal duration) and 3·6 days (120 V/m voltage gradient, 24 h polarity reversal duration) for samples treated with EO to achieve 90% consolidation, while it took 16 days for the sample that had not undergone electro-osmotic consolidation to achieve 90% consolidation.

(*b*) An increase of 11·6–58% in shear strength was attained for the specimen treated with EO. Conversely, the sample with PVDs but without EO had only gained 9·8–19·5% increase in strength.

(*c*) The polarity reversal technique must be employed during electro-osmotic consolidation in order to gain a more uniform development of the soil between the location of the electrodes. A larger voltage gradient (120 V/m) coupled with a longer polarity reversal interval (24 h duration) showed a higher difference in shear strength between the electrodes.

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Discussion contributions on this paper should reach the secretary by 10 January 2001