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Soft Soil Improvement by Electroosmotic Consolidation

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Abstract: Many laboratory experiments and field trials have shown the potential of electroosmotic consolidation in strengthening of soft clays. However, there are no detailed studies on the effectiveness of electroosmotic consolidation in peat and organic soils. The paper discusses first the electrokinetic reactions that occur during electrokinetic treatment and the material and treatment parameters that affect the effectiveness of the treatment. A review of the laboratory studies is presented. Salient features of the laboratory experimental studies to investigate the effectiveness of the electroosmosis technique in improving peats and an organic soil from Sarawak are then presented. The influence of selected treatment parameters on the electroosmosis phenomenon is also discussed.

Keywords: Electroosmotic consolidation, electrokinetics, peat, soft soil, soil improvement

1. Introduction

In electrokinetic treatment of soft soils a low direct current or a low potential gradient is applied across a pair of positive (anode) and negative (cathode) electrodes inserted into the soil (Fig. 1). The application of voltage gradient can lead to several electrokinetic reactions. Electrophoresis is one of the reactions in which charged colloids present in the solid-liquid mixture tend to migrate towards the oppositely charged electrode. Electro migration or ion migration is another reaction in which charged ions tend to move towards the oppositely charged electrode. Electroosmosis is the reaction in which there is transport of pore water through the voids in the soil whereas ion migration can occur potentially without any fluid flow. Electrolysis is another reaction in which oxidation and release of oxygen take place at the anode and reduction and generation of hydrogen take place at the cathode.

Electrophoresis and electroosmosis play an important role in the sedimentation of particles in high water content mining tailings and sludge and increasing their solids content. Ion migration and electroosmosis play a significant role in geoenvironmental engineering applications such as remediation of contaminated groundwater and soil. The important applications of electroosmosis in geotechnical engineering are in dewatering and improvement of soft soils through consolidation.

2. Electroosmotic Consolidation

The surface of clay particles has a net negative charge. The major cations present in the pore water are Na^+, Mg^{2+} and Ca^{2+}. The negative surface charge of the clay particle is balanced partly by the adsorption of cations in the pore water on the surface of clay particles (Fig. 2). The adsorbed cations may be exchanged with other cations in the pore water. Therefore, they are also called as exchangeable cations. A water molecule H_2O made of one oxygen atom and two hydrogen atoms is electrically neutral. However, because of the asymmetric arrangement of the hydrogen and oxygen atoms, the water molecule behaves as a dipole molecule; the side with the oxygen atom has a partial negative charge and the other side a partial positive charge. The negative surface charge of the clay particle is balanced partly by the adsorption of dipole water molecules (Fig. 2) called adsorbed water. The cations in the pore water also attract dipole water molecules and form hydrated cations. The hydrated cations are attracted to the oppositely charged electrodes. They drag the surrounding free water molecules along with them. The net water movement or electroosmotic flow is towards the cathode where the water drains out causing consolidation of the soil.

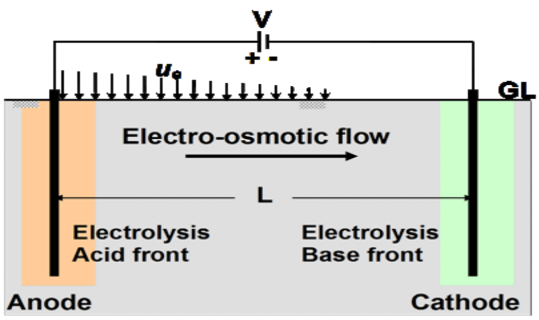

Fig. 1 Electroosmosis and electrolysis reactions [1].

The rate of electroosmotic flow, q_e, through cross-sectional area of flow A is expressed as [2]:

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$$q_e = k_e\, i_e\, A \tag{1}$$

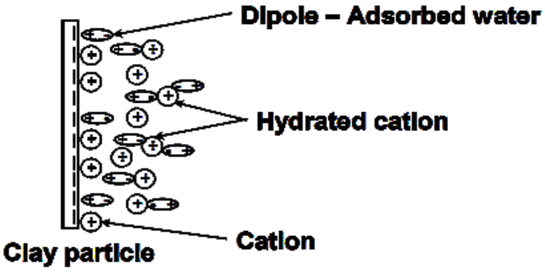

Fig. 2 Clay particle–pore water system.

In Equation (1), k_e is the electroosmotic coefficient of permeability. The k_e of clay soils is in the range of 10^{-9} m^2/sV. According to Asadi et al. [3], the k_e value of Malaysian peats is in the range of 10^{-9} to 10^{-10} m^2/sV. In Eq. 1, i_e is the voltage gradient ($\Delta V/\Delta l$). ΔV is the voltage drop over a current flow path of Δl. The voltage gradient typically ranges from 10 to less than 100 V/m in field applications [4]. Electroosmosis is effective when the ratio k_e/k_h, (k_h is the hydraulic coefficient of permeability) is high [5].

The electroosmosis process also induces changes in pore water pressure. In a uniform electric field when the anode is closed to supply of water and cathode is open to drainage the pore water pressure due to electroosmosis is given by,

$$u_e(x) = -\frac{k_e \gamma_w}{k_h} i_e x \tag{2}$$

where γ_w = unit weight of water and x = distance from the cathode towards anode. Equation (2) shows that electroosmosis induces a negative excess pore water pressure which is maximum at the anode.

Electrolysis reactions accompany electroosmosis and produce acidic and basic conditions at the anode and cathode, respectively. The acidic and base fronts migrate towards each other. Fig. 1 shows the reactions in the soil-water system due to electroosmosis and electrolysis.

Electroosmotic consolidation is the result of progressive removal of water at the cathode. It is akin to consolidation caused by dissipation of excess pore water pressure. Therefore, electroosmotic consolidation can be used as a soil improvement technique to increase the shear strength and reduce the compressibility of soft soils. The effectiveness of electroosmotic consolidation, however, depends on the material parameters and treatment parameters.

2.1 Material or Soil-Pore Water Parameters

The important material properties that influence electroosmotic consolidation are the electric double layer (EDL) and zeta (ζ) potential which in turn are affected by other factors such as increase in the cation concentration, valence of cation, size of cation, pH, and temperature. EDL is a minute thickness layer of pore water surrounding the clay particle in which there is a net negative charge. The negative charge decreases from maximum at the surface of the clay particle to zero at the DDL-free water interface. It is also called the diffuse double layer (DDL). The ions in the EDL are predominantly cations and hydrated cations. The thickness of EDL decreases with an increase in the cation concentration, valence of cation, and size of cation. The thickness of EDL increases with an increase in temperature. Electroosmotic flow increases as the thickness of EDL increases.

A part of EDL adjacent to the clay particle constitutes the immobile pore water which cannot be moved by tangential stresses. A shear plane separates the immobile portion and mobile portion of the EDL. The net electric charge at the shear plane is known as ζ-potential (zeta potential) or the electrokinetic potential. The ζ-potential is affected by pH, generally increases as pH increases. Yukselen and Kaya [6] reported that the ζ-potential of kaolinite in water became more negative as pH increased and ranged from −25 mV at pH = 3 to −42 mV at pH = 11. They also found the ζ-potential to be sensitive to the concentration and valence of ions. A similar trend was reported by Asadi et al. [7] for a peat sample from Selangor in Malaysia; the ζ-potential of the peat increased from nearly zero at pH = 3 to −39 mV at pH = 11.5. The ζ-potential also became more negative with increasing degree of decomposition of peat. Table 1 shows the relationship between ζ-potential and stability of suspension [8].

Table 1 Relationship between ζ-potential and stability of suspension [8]

Stability characteristics	Average ζ-potential, mV
Maximum agglomeration	0 to +3
Strong agglomeration	+5 to −5
Threshold of agglomeration	−10 to −15
Threshold of delicate stability	−16 to −30
Moderate stability	−31 to −40
Fairly good stability	−41 to −60
Very good stability	−61 to −80
Extremely good stability	−81 to −100

Shang [9] reported k_e to be proportional to the ζ-potential expressed by,

$$k_e/n = -\,2.84 + 0.0634\,\zeta \tag{3}$$

In Equation (3), n is soil porosity and the units of k_e and ζ are m^2/sV and mV, respectively. The ζ-potential reported by Shang for ten clays ranged from 22 to 147 mV while the pH values ranged from 6.3 to 9.2. The ζ-potential values were not only high but also positive. The ζ-potential values were probably reported erroneously as positive instead of negative. Using Shang's data and assuming the ζ-potential values as negative, the empirical correlation for k_e can be expressed by Eqs 4 and 5.

$$k_e = -1.249 - 0.0364\,\zeta \quad (4)$$

$$k_e/n = -1.88 - 0.0573\,\zeta \quad (5)$$

The coefficient of determination R^2 value of Eqs 4 and 5 is close to 0.92. Equations (4) and (5) suggest that $k_e = 0$ or there is no electroosmotic flow when ζ-potential is about −33 to −34 mV, which is not realistic. Therefore, Eqs 3 to 5 are not recommended as good correlations between k_e and ζ-potential.

2.2 Electrokinetic Treatment Parameters

The treatment factors that influence the effectiveness of electroosmotic consolidation are: type of electrode, voltage gradient, polarity reversal, current intermittence, and duration of treatment.

Electrical conductivity and durability are important factors in the selection of electrodes. Metals are very good conductors of electricity. Copper, mild steel and stainless steel in different shapes and forms such as rod, mesh, tube, and perforated or slotted tube have been used as electrodes. However, metallic electrodes are vulnerable to corrosion and severance of continuity particularly at the anode where acidic conditions are created due to electrolysis reaction. New types of geosynthetics called electrokinetic geosynthetics (EKG) used in electroosmotic consolidation applications provide electrokinetic function in addition to the filtration and drainage functions. The EKG electrodes are less susceptible to corrosion due to the polymeric cover or treatment against corrosion. Prefabricated electric vertical drains (EVD or ePVD) with metallic electrode encapsulated in polymeric core or with exposed conductors are available.

As mentioned earlier, the voltage gradient, i_e, used in field applications is typically in the range of 10 V/m to less than 100 V/m [4]. The voltage gradient may be maintained constant throughout the treatment period or it can be varied over the duration. In variable voltage gradient, the voltage gradient is increased in steps from a low value in the beginning to higher values as the treatment progresses in order to reduce the energy consumed during the soil treatment.

The voltage gradient may be applied maintaining the polarity of anode and cathode the same during the treatment period. In this method of treatment, the electroosmotic flow is constantly in one direction from anode to cathode. As a result the treated soil has non-uniform characteristics. The water content of the treated soil is the lowest near the anode and increases towards the cathode, the shear strength decreases from anode to cathode, and the soil compressibility increases from anode to cathode. In order to have a more even ground improvement, the polarity of the electrodes may be reversed during the course of treatment which will cause the osmotic flow to occur in the opposite direction. However, Kaniraj et al. [10] in a laboratory study on peats, Bjerrum et al. [11] in a field study on Norwegian quick clay deposit, Ou et al. [12] in a field study at Taipei, and Chien et al. [23] in a laboratory study on Taipei clay reported that polarity reversal did not produce favorable effects in terms of water discharged from cathodes and improvement in undrained strength. Kaniraj et al. [10] attributed the unfavorable effect of polarity reversal to drying of soil and the acidic conditions that prevailed near the anode. If the soil near anode is unsaturated before polarity reversal it needs to be saturated again when it becomes cathode to sustain the electro-osmotic flow in the reverse direction. Further, acidic conditions near the anode, before its polarity reversal to cathode, reduce the ζ-potential of the soil and thereby the potential for electro-osmotic flow. Thus, the effectiveness of polarity reversal will depend on the polarity reversal interval, which should not allow the unsaturation of the soil near the anode and drastic reduction in its ζ-potential to set in.

Applied voltage gradient can be held constant without interruption during the treatment period. Alternatively, the voltage gradient can be applied intermittently in *on-off* pulses, for example 2 minutes *on* and 1 minute *off*. Mohamedelhassan and Shang [13] reported that current intermittence had a significant effect on electroosmotic flow. Like variable voltage gradient explained before, current intermittence reduces the energy consumption of soil treatment.

The duration of electroosmotic consolidation in the field depends on factors such as initial conditions of the soil (e.g. initial water content, initial undrained strength), the improvement targets (e.g. amount of settlement, final undrained strength, final water content), applied voltage gradient, and manner of application of voltage gradient (e.g. constant or variable gradient, with or without polarity reversal, with or without current intermittence). Compared to the conventional methods of ground improvement such as preloading with vertical drain, electroosmotic consolidation has caused significant ground improvement in a relatively short time [14, 15].

Several laboratory experiments and field trials have shown the potential of electroosmotic consolidation in strengthening of soft clays. A review of the laboratory studies is presented in the following sections.

3. Laboratory Experimental Studies

3.1 Anode Closed−Cathode Open Condition

Shang et al. [16] carried out experiments on marine sediments from Matagorda Bay of the Texas Gulf Coast. The sediment had 71% clay size content. The liquid limit, plastic limit and plasticity index were 93.5%, 54.5%, and 39, respectively. The electrodes consisted of 4.8 mm diameter copper rod inside a 13 mm outer diameter Plexiglas tubing filled with mineral transformer oil. Two groups of experiments were conducted. In the first group of experiments the effect of high-voltage AC and DC field on the marine sediment was investigated. For AC field, a transformer with an output voltage of 15kV at 60 Hz frequency and maximum current of 60 mV was used. For DC field, a high-voltage supply model with output voltage 0 to ±50 kV and output current 0 to 2 mA was used. In the second group of experiments, 300 x 152 x 3.2 mm steel plates were embedded in the sediment and the effect of high-voltage fields on the pullout resistance of the plates was investigated. Different durations of application of electric field were used in the experiments. The high-voltage electricity fields increased the shear strength of the marine sediment and the pullout resistance of the embedded steel plate considerably. Effects due to high voltage negative DC fields were more significant than due to high-voltage AC fields. The researchers also pointed out that the effects of high-voltage electrokinetics were irreversible even long after the stoppage of the electric fields.

Bergado et al. [17,18] carried out experiments on undisturbed and reconstituted soft Bangkok clay. The clay had 19% silt size and 79% clay size contents. The liquid limit, plastic limit and plasticity index were 96%, 33%, and 63, respectively. In the control test the specimen was consolidated under a vertical pressure with prefabricated vertical drains (PVD) installed in the specimen. In the electroosmotic experiments, direct current was also applied in the specimens. Copper and carbon electrodes were used. The electrodes consisted of eight 13.6 mm diameter copper or carbon rods inserted into the core of PVD and covered by geotextile filter. Voltage gradients of 60 V/m and 120 V/m were applied. The polarity was reversed at every 24 h. The tests were continued until 90% average degree of consolidation was reached as determined by Asaoka's method [19]. The electroosmosis and PVD (EO-PVD) combination had a greater effect on consolidation than PVD alone. EO-PVD combination increased the settlement of specimens with PVD only by 27 to 101%. The reduction in water content in specimens with PVD only was about 3%, whereas in the case of EO-PVD combination the reduction in water content was about 5 to 9%. The time to achieve 90% average degree of consolidation by the EO-PVD combination was 1.2 to 2.2 times faster than by PVD alone. The increase in shear strength due to EO-PVD combination ranged from 25 to 144%, whereas the increase in the case of PVD only was in the range of 15 to 26%. Electrokinetic treatment increased the Atterberg limits; the increase in liquid limit was up to 7%, plastic limit up to 6%, and plasticity up to 8. The researchers also noted that carbon electrodes performed better than copper electrodes in terms of reduction in water content and increase in shear strength.

Lefebvre and Burnotte [20] carried out experiments on clay samples from Mont St. Hilaire, Quebec, and studied the conditions that affected power loss at the soil-electrode contact. They used perforated steel tubes as electrodes to allow flow of gas and water. A total of five tests were carried out. In three tests the anodes were chemically treated by injection of a saline solution in the beginning of electrokinetic treatment, in the other two tests the anodes were not chemically treated. The voltage gradient was maintained constant at 35 V/m in four tests and in one test the voltage gradient was varied from 30 V/m in the beginning to 37 V/m at the end of the test. The study showed that the chemical treatment of anode decreased the power loss significantly and doubled the voltage gradient. In one of the tests with chemically treated anodes, the undrained strength increased from 47 kPa initially to an average value of 123 kPa. In another test with chemically treated anodes, the undrained strength increased from 29 kPa initially to an average value of 58 kPa.

Hamir et al. [21] carried out experiments to assess the performance of EKG materials in electroosmotic consolidation and reinforcement. The EKG electrode used for consolidation consisted of a conductor, a filter and a drain. The EKG electrode used for reinforcement consisted of a conductor and a permeable or impermeable reinforcement. Four different types of EKG electrodes, three of them planar material and one a linear element, were used. The four types electrodes were: *a*) a needle punched geosynthetic material with a copper wire stringer, *b*) a needle punched geosynthetic material with stainless steel fibers, *c*) a composite polypropylene and carbon fiber sheet, and *d*) geocomposite strip reinforcement with a copper wire stringer. Copper discs were used as control electrodes and as a benchmark to assess the efficiency of the EKG electrodes. All tests were carried out by mixing kaolin with distilled water to slurry form. The liquid limit, plastic limit, and plasticity index of the kaolin were 55%, 34% and 21, respectively. Electroosmotic consolidation tests were carried out in a 150 mm diameter and 230 mm height cell. Tests were conducted at different voltage gradients in the range of 25 to 170 V/m and at different values of constant current. Electroosmotic consolidation was also combined with vertical stresses of 50 or 100 kPa acting on the sample. Drainage was allowed either one-way at cathode end only or two-way at both the anode and cathode ends. Electroosmotic tests were also conducted with polarity reversal in three ways: applying *a*) the same voltage applied before polarity reversal, *b*) twice the voltage applied before polarity reversal, and *c*) one-half the voltage applied before polarity reversal. The researchers concluded that that the performance of EKG electrodes was comparable to the copper disk electrodes and the EKG electrodes were fully effective in all types of tests carried out.

Chew et al. [14] carried out experiments on 20 mm thick specimens in a modified oedometer and also on 500 mm diameter and 150 mm thick large specimens. Tests were carried out on Singapore marine clay which had silt size and clay size contents of 46% and 44%, respectively. The liquid limit, plastic limit and plasticity index were 80%, 35% and 45, respectively. Two oedometer tests were carried out at voltage gradients of 100 and 150 V/m Stainless steel electrodes were used. One control test was carried out without voltage gradient. There was an apparent decrease in coefficient of consolidation c_v, compression index C_c, and coefficient of secondary compression C_α due to electroosmotic treatment. In the large specimen tests voltage gradient of 67 V/m was applied. Perforated metal plate electrodes were used. The initial undrained strength of the specimen after it was consolidated under 31 kPa was about 8 kPa. After electrokinetic treatment the undrained strength increased to 26-35 kPa near the anode, 14-15 kPa near the cathode, and 10 kPa midway between anode and cathode. Electrokinetic treatment decreased the compressibility of the clay. The void ratio-effective stress (e-logσ') curves from consolidation tests carried out on samples before and after electroosmotic consolidation showed significant decrease in compression index C_c and coefficient of recompression C_r.

Naggar et al. [22] carried out experiments on simulated marine sediment to investigate the response of model piles to lateral and cyclic loads. The soil from London, Ontario, Canada, had about 42% clay size and 24% silt size particles. The soil was dried, crushed and mixed with sodium chloride solution at 10 g/l concentration. The soil slurry was poured inside two cylinders of internal diameter 1.37 m and depth 1.52 m in layers and consolidated under vertical pressure of 30 kPa. The liquid limit and plastic limit of the consolidated sediment were 43% and 33%, respectively. Four piles were installed in each cylinder. One of the test cylinders was used for control tests without electrokinetic treatment. In the other cylinder one copper rod was installed close to each pile and one copper rod was installed at the centre of the 4 piles as electrodes. High-voltage electrokinetic treatment was made in three phases. The soil was treated by −20 kV, −30 kV and −10 kV DC voltage of negative polarity in phase I, phase II and phase III, respectively. The treatment period was 33 days in each phase. At the end of each phase lateral and cyclic load tests were carried out on one pile in both cylinders and the responses of the control test pile and pile after electrokinetic treatment were compared. It was observed that the lateral load capacity of the piles increased by 81, 60, and 12%, respectively, after the first, second and third phases of electrokinetic treatment. The increase in the undrained strength of the soil was perhaps a reason for the improvement in the response of the piles. For example, in phase I experiment the average undrained strength increased by 13% in the electrokinetic test cylinder but only by 6% in the control cylinder, due to aging effects. The increase in the undrained strength of soil close to the piles was higher due their proximity to the anodes.

Chien et al. [23] studied the effect of injection of chemical solutions and electrokinetics on improvement of Taipei silty clay. The soil had 86% and 12% of silt and size particles, respectively. The liquid limit, plastic limit and plasticity index were, 46%, 30% and 16, respectively. The soil was ground into powder and then mixed with distilled deionized water to a water content of more than 1.5 times liquid limit. The slurry was then placed in a cell similar to the one used by Beregado [17] and consolidated under a pressure of 100 kPa until 95% average degree of consolidation was reached. The average water content and undrained strength of the specimen after consolidation were 35% and 20 kPa, respectively. Perforated stainless steel tubes, 10 mm diameter, 420 mm length, and 1 mm holes drilled at 5 mm spacing, were installed as electrodes for injection of chemicals at the anode and drainage of fluid at the cathode during the electroosmotic stages. A total of six experiments were carried out at voltage gradient of 50 V/m. In the first test, only the voltage gradient was applied for 7 days. The average undrained strength after treatment increased to 39 kPa. In the other five experiments calcium chloride solution ($CaCl_2$) with 1 N concentration and sodium silicate solution ($Na_2O.nSiO_2$, n = 3.4) with a sodium silicate volume/water volume ratio of 1:10 were injected at the anode at a pressure of 20 kPa. In the second experiment, calcium chloride solution was injected for 1 h which was followed by application of voltage gradient for 7 days. At the end of treatment the average undrained strength was 49 kPa which indicated the favorable influence of the short term injection of calcium chloride solution prior to electrokinetic treatment. In the third experiment, calcium chloride solution was injected for 7 days simultaneously with the application of voltage gradient. At the end of treatment the average undrained strength was 25 kPa which indicated the unfavorable influence of continuous injection of calcium chloride solution along with electrokinetic treatment. In this case the experimental condition is equivalent to anode open-cathode open condition. In the fourth experiment, calcium chloride solution was injected first for 2 days followed by injection of sodium silicate solution for the next 2 days and then the voltage gradient was applied for 3 days. The fifth experiment was similar to the fourth experiment except for the sequence of injecting the sodium silicate solution first followed by injection of calcium chloride solution. At the end of treatment the average undrained strengths were 59 and 58 kPa in the fourth and fifth experiments, respectively, which indicated the favorable influence of long duration schemes of injection of chemicals before electrokinetic treatment. In the sixth experiment the effects due to polarity reversal were investigated. In this experiment the procedure as described for the fourth experiment was completed first. The voltage gradient was then terminated. Calcium chloride solution was then injected for 2 days followed by injection of sodium silicate solution for the next 2 days. The voltage gradient was then applied for 3 days with the polarity reversed. At the end of treatment the average undrained strength was 46 kPa which indicated the unfavorable influence of polarity reversal. The researchers explained that the cementation near the anode before polarity reversal did not permit drainage of water when it became cathode which led to a consequent increase in water content in soil and reduction in shear strength.

3.2 Anode Open−Cathode Open Condition

Ozkan et al. [24] carried out experiments on kaolinite beds by circulating 1 M phosphoric acid solution at anode and cathode in one experiment and 0.5 M phosphoric acid solution at cathode and 0.5 M aluminum sulphate solution in another experiment. A constant current of 90 mA was applied through the kaolinite beds for 21 days. An average increase in shear strength of 500 to 600% was observed. Since the experiments were conducted at anode open–cathode-open condition, the stabilization of kaolinite depended on the transport of ions and not due to changes in water content. The increase in shear strength due to change in water content was small in the range of 0−22%. The electrokinetic treatment also caused an average 30% increase in the Atterberg limits of kaolinite. The researchers attributed the cause of increase in Atterberg limits and shear strength to modification of the pore fluid by the phosphate and aluminum ions and to mechanisms of ion exchange and precipitation.

Mohamedelhassan and Shang [13] carried out a series of experiments on a marine sediment from south-west coast of Korea to investigate the effects of electrode materials and current intermittence on k_e and voltage loss at the soil-electrode interfaces. The marine sediment had 66% silt size and 23% clay size contents. The liquid limit, plastic limit and plasticity index were 59%, 32%, and 27, respectively. The marine sediment bed was first consolidated under a surcharge of 9.3 kPa. Then designated voltage gradients were applied across the sediment bed for 8 hours. The electrode consisted of prefabricated vertical drains with mesh core. Distilled water mixed with NaCl and NaOH at salinity of 8 g/l and pH of 7.6 were kept in the reservoirs at the anode and cathode ends. The solution was circulated through the marine bed under anode open–cathode open condition. Six different anode-cathode material combinations namely carbon-carbon, carbon-steel, carbon-copper, steel-carbon, steel-steel, and copper-copper were used. Five different voltage gradients varying from 16 to 60 V/m were applied. In the current intermittence experiments, several On/Off combinations (in minutes) namely 1/0.5, 2/1, 3/1.5, 4/2, and 5/2.5 were used. The researchers concluded that k_e was a function of the electric field intensity but was independent of the electrode materials. k_e increased with increase in the applied voltage nonlinearly and reached a plateau at a higher voltage. Current intermittence enhanced the electroosmotic flow, which manifested as a higher value of k_e.

Yeung [25] carried out experiments on a Milwhite kaolinite specimen to investigate the effect of the chemistry of pore fluid at anode and cathode on the direction of electroosmotic flow. The combined clay and silt size content of the kaolinite was 94%. The liquid limit, plastic limit and plasticity index were 46%, 25% and 21, respectively. The experiment was done in eight stages for a total duration of 517.46 h. Each stage was identified by either the introduction of a new chemical solution in the reservoirs at the electrodes or a change in the direction of electroosmotic flow. The duration and applied voltage gradient were not the same for each stage of the experiment. The duration varied from 9.85 to 155.84 h and voltage gradient varied from 65.35 to 262.47 V/m. The different chemical solutions used were $NaHCO_3$ at pH 9, 0.01 M acetic acid CH_3COOH, and deionized water. Yeung concluded that depending on soil pH and pore fluid chemistry the direction of electroosmotic flow can be reversed during a prolonged electrokinetic process. Soil pH was the predominant factor in controlling the direction of electroosmotic flow. The k_e measured in short-duration experiments were constant with time and were in the range of 10^{-8} to 10^{-9} m2/sV. Further, k_e did not depend on the voltage gradient. Probably the voltage gradients in the experiments of Yeung were high enough that the k_e had reached the maximum constant value as suggested by Mohamedelhassan and Shang [13].

4. Laboratory Experimental Studies on Peats and Organic soils of Sarawak

Several laboratory experimental studies have shown that electroosmotic consolidation is an effective ground improvement technique in fine grained soils. Several field trials have also demonstrated this. However, there are not many studies reported on the effectiveness of electroosmotic consolidation in peat and organic soils. The following section describes the salient features of the experimental studies carried out by the author on peats and an organic soil from Sarawak, Malaysia. More details are available in [1] and [10].

The overall aim of the study was to investigate the effectiveness of the electroosmosis technique in improving peat and soft organic soils. The specific objectives included the evaluation of influence of selected parameters on the electroosmosis phenomenon in peat and organic soils.

4.1 Materials

One peat sample from a location along the Miri-Marudi road and another peat sample from Similajau and an organic soil from Sibu were collected. A clayey silt sample with low organic content also was used as a reference material. Fig. 3 to Fig. 5 show the scanning electron micrographs of the peats and organic soil. Table 2 shows more properties of the peats and the organic soil.

A commercially available prefabricated EVD was used as electrodes. It consisted of a copper foil encapsulated in a conductive polyethylene core.

Fig. 3 Scanning electron micrographs of Miri-Marudi peat [1,10].

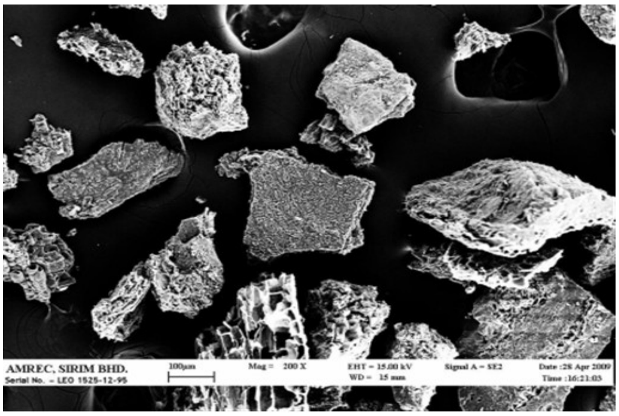

Fig. 4 Scanning electron micrographs of Similajau peat [1,10].

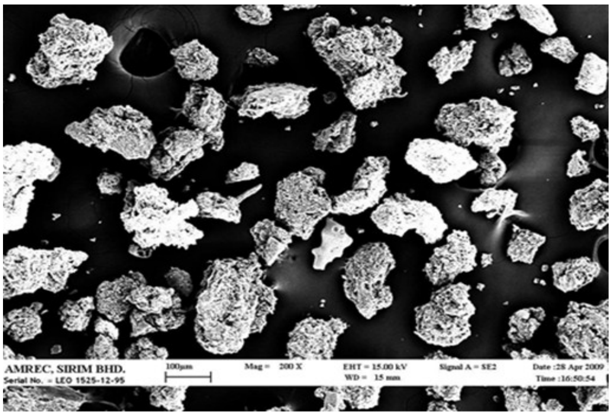

Fig. 5 Scanning electron micrograph of Sibu organic soil [1,10].

Table 2 Geotechnical properties of peats and soils [1, 10]

Property	Miri-Marudi peat	Similajau peat	Sibu organic soil	Clayey silt
Natural water content, w_n (%)	552	643	87	-
Organic content, N (%)	97	96	49	11
Von Post classification	H8	H8	-	-
Specific gravity, G	1,47	-	-	2.56
Liquid limit, w_l	413	323	245	62
Plastic limit, w_p	257	244	155	43
Plasticity index, PI	156	79	90	19

4.2 Apparatus

Fig. 6 and Fig. 7 show the details of test tanks used in the experiments. The pore water in the case of peat beds was removed from the test beds through flexible tubes connected to a hole located close to the floor of the test tank in the two end walls. The pore water flowed out continuously during the experiment. In the experiments on Sibu organic soil, the pore water was pumped out from drain pipes shown in Fig. 7(b) which simulated ejector wells used in the field.

4.3 Experimental Procedure

The experimental procedure involved: a) preparation of test materials, b) preparation of test beds, and c) carrying out self-weight and electroosmotic consolidation tests simultaneously. The details of the measurements for a) initial and final undrained strength, b) initial and final water content distribution, c) deformation of the surface of the test bed, d) volume of drained water, and other details are explained in [1, 10]. In a series of tests the influence of several parameters on electroosmotic consolidation was studied. Table 3 shows a summary of the parameters investigated.

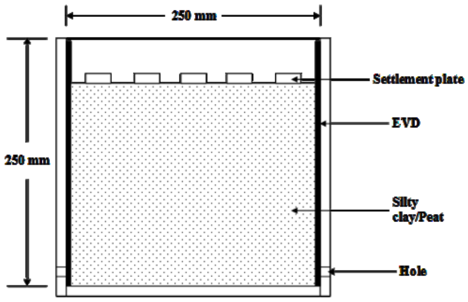

Fig. 6 Test tank with drainage at the bottom of the test bed.

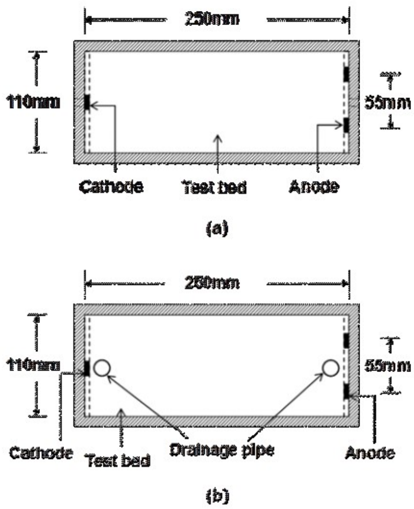

Fig. 7 Plan of test tank showing the 2anodes-1cathode configuration: (a) Drainage at bottom of test bed (b) Drainage through drainage pipe [10].

Table 3 Test parameters and the range of values [1, 10]

Parameters	Range or variation
Voltage gradient	0[a] – 180 V/m
Configuration of EVD	Full width[b], 1-1[c], & 2-1[d]
Roots	Present, Absent[e]
Polarity reversal	No polarity reversal, & 8 – 24 h[f]
Pumping interval	3 – 12 h[g]

[a]0 V/m refers to self-weight consolidation tests in which no voltage gradient was applied. [b]The EVD nearly covered the full width of the test bed at the anode and cathode ends. [c]One 15 mm wide EVD strip was used at both anode and cathode ends. [d]Two 15 mm wide EVD strips were used at the anode and one 15 mm wide EVD strip was used at the cathode (Fig. 7). [e]Long roots present in the peat samples were removed before preparing the test bed. [f]The polarity of the electrodes were reversed at the specified intervals of time. [g]In tests with plastic drainage pipes in the test beds (Fig. 7b).

4.4 Results

Table 4 shows typical results of the influence of voltage gradient on the outcomes of electro-osmotic consolidation of Similajau peat. From the results in Table 4 and from other tests it was inferred that the voltage gradient had a significant effect on the outcome of electroosmotic consolidation. The volume of water drained from the test beds and the undrained strength generally increased as the voltage gradient increased. The maximum voltage gradient for optimum results appeared to be in the region 120 V/m.

Table 4 Influence of voltage gradient on electro-osmotic consolidation of Similajau peat [1, 10]

Property	Voltage gradient, V/m			
	80	100	120	140
Initial water content (%)	554	555	552	554
[a]Total volume of water drained, ml	1160	1340	1610	1466
[b]S_{ui}, kPa	2.25	1.32	0.92	1.32
[c]S_{uf}, kPa	11.47-18.80	10.89-24.42	15.34-34.04	8.77-28.69
Maximum increase in S_u, (%)	736	1750	3600	2073

[a]Duration of each test was 8 days and 2anodes-1cathode configuration was used in all tests. [b]Initial undrained strength. [b]Final undrained strength (increases from cathode to anode).

Fig. 8 shows the results of water drained from the Sibu organic soil test beds which had initial water content in the range of 219-221%. In the self-weight consolidation test bed (12 h pumping interval), 138 ml of water flowed out. Under a voltage gradient of 80 V/m and 3 and 6 h pumping intervals, 1014 and 991ml of water drained out, respectively.

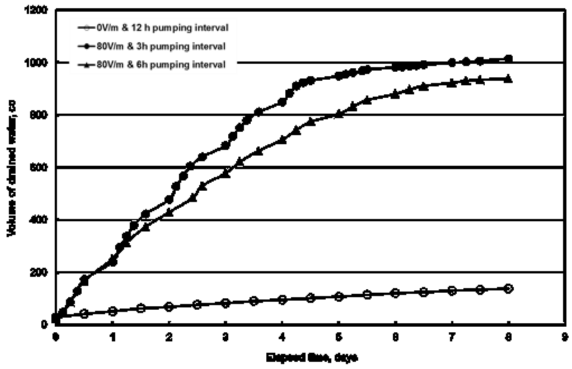

Fig. 8 Influence of pumping interval on the volume of water drained from Sibu organic soil test beds.

Fig. 9 shows the comparison of water drained from four Sibu organic soil test beds. The voltage gradient was 80 V/m and the pumping interval was 3 h in all the test beds. The initial water content of the test bed in which there was no polarity reversal was 221%. In the other 3 beds where polarity was reversed at 8, 12, and 24 h intervals the initial water content was in the range of 249-254%. As Fig. 9 shows, polarity reversal resulted in significantly lesser electroosmotic flow. The volume of water drained from test beds with no polarity reversal, and with polarity reversal at 8, 12, and 24 h intervals were 1014, 608, 607, and 623 ml, respectively.

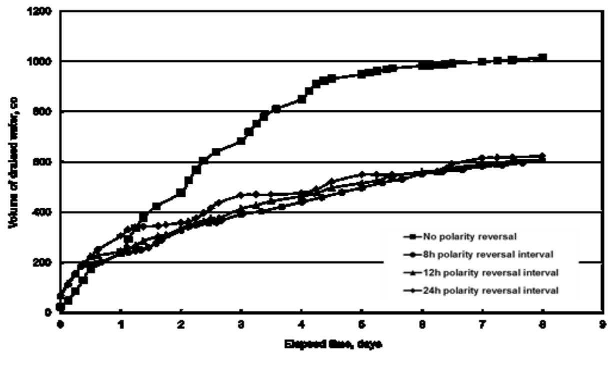

Fig. 9 Influence of polarity reversal on the volume of water drained from Sibu organic soil test beds [1].

5. Conclusions

Based on the results of the laboratory electroosmotic consolidation experiments on soils, peats, and organic soil, the following conclusions are made.

1. Electroosmotic consolidation is an effective technique to improve the undrained strength of soft fine grained soils, peats and organic soils.

2. The effectiveness of electrokinetic treatment of soft soils and peat depends on material parameters characterised by the ζ-potential and pH of soil.
3. The effectiveness of electrokinetic treatment also depends on treatment parameters such as voltage gradient, current intermittence, polarity reversal, injection of chemical solution at the electrodes, and duration of treatment.
4. The voltage gradient had a significant influence on the results of electroosmotic consolidation. The electroosmotic flow and undrained strength generally increased as the voltage gradient increased. The maximum voltage gradient for optimum results appeared to be in the region 120V/m.
5. When ejector wells are used near cathode, shorter pumping interval resulted in more and faster electroosmotic consolidation.
6. Polarity reversal resulted in significantly lesser electroosmotic flow and soil improvement.

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