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ORIGINAL PAPER

Influence of boundary conditions on transient excess pore pressure during electrokinetic applications in soils

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Abstract Application of electric currents through saturated silt and clay-rich soils induces electrochemical effects that influence the mechanical and hydraulic behaviour of soft soils. The transient effects of electro- and geo-chemical changes on pore pressure evolution in soil are poorly understood. A major issue, the transient development of non-linear geo- and physico-chemical conditions between the electrodes, is evaluated in this study. An experimental investigation was conducted to provide an understanding of the mechanisms that affect pore pressure or suction development along the sample and consequent transient and non-linear changes. A natural silty soil was used because it accounts for the complex physical and chemical interactions that originate during treatment in the field. Tests were conducted with free drainage at the boundaries and under constant current intensity. The experimental investigation results highlighted the importance of the boundary chemical conditions on the development and transient changes in excess pore pressure along the sample. In particular, the generation of high potential gradients in the first few millimetres of the soil sample dominates the overall pore pressure distribution and behaviour. A relationship between the maximum pore pressure developed and the applied current density is evaluated.

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1 Introduction

The investigation of electrokinetic phenomena in soils could be dated to early nineteenth century, though it was not applied to geotechnical engineering until late 1930s when Leo Casagrande [1] engineered electroosmotic soil consolidation and dewatering. Around mid 1980s the attention shifted to engineering electrokinetic phenomena for remediation of contaminated soils [2–6]. The technique has shown to be particularly effective for silt- and clay-rich soil that is characterised by low hydraulic conductivity and electrically charged particles. Most studies on electrokinetic treatment have been limited to laboratory experiments with reconstituted soil, typically kaolin. A few field and pilot scale studies have demonstrated the success of the process in removing heavy metals and organics from contaminated soils, though some have shown limited success [7–10]. In situ applications have been challenged by the complex and heterogeneous field conditions.

Since in general the goal of electrokinetic remediation is extraction or treatment of chemical contamination in soil, the influence on the transient hydraulic and mechanical behaviour of the treated soil has been rarely considered. Moreover, laboratory testing has been conducted mostly on mono-mineral soils. Though this allows better understanding of the electrochemical interpretation of the results, it can lead to misleading conclusions regarding the practicality of field application. The heterogeneous results that are typically obtained when testing natural soil, or conducting pilot tests and field demonstrations, suggest that the particular physical and chemical properties characterising each soil greatly influence its transient response.

The presence of diffuse double layer in a soil–water–electrolyte system results in four principal flows: water, chemical, electric and heat flow. Water flow is the most relevant, due to its essential role in the majority of geotechnical engineering applications, such as seepage, consolidation and stability. Nevertheless, the growing importance of geoenvironmental problems related to pollution, waste disposal, and contaminant remediation highlights the importance of the coupling effect of chemical transport and reactivity.

Leo Casagrande [1] showed that fine grained soils exhibit a relatively uniform electroosmotic flow rate, defined by the coefficient of electroosmotic permeability, k_e, under electric fields, expressed as:

$$q_e = k_e \frac{\Delta E}{L}$$

where q_e is the electroosmotic flow rate and $\Delta E/L$ is the voltage gradient. The value of k_e typically varies within one order of magnitude for different fine grained soils. Researchers and engineers applied the concept of the empirical constant k_e in predicting rates of electroosmotic consolidation and dewatering [11–13]. The concept has also been considered to improve soil strength. Soil hardening by electrokinetics has been related to several coupled processes including physico-chemical adsorption and desorption, ion exchange, structural changes of clay aggregates and excess pore pressure generation [12, 14–16].

Besides the engineering macroscopic approach, a microscopic approach has been carried out, principally by colloid scientists and surface chemists. The classic studies have shown a dependence of electrokinetic response on the electrolyte concentration, pH, and the characteristics of the solid medium [17, 18]. A useful link between the phenomenological and more fundamental methods is represented by the relationship:

$$k_e = \frac{-\varepsilon \zeta n_e \tau}{\mu} F(\kappa \alpha)$$

where n_e is the effective porosity, τ is the tortuosity defined as the square of the ratio of the length of the specimen to that along the flow path, ε is the permittivity of the fluid, ζ is the zeta potential, κ is the inverse Debye length, α is the radius of the capillary and $F(\kappa \alpha)$ is the Rice and Whitehead electroosmosis correcting factor [19].

The macro- and microscopic approaches to understand electrokinetic phenomena in soil show the dependence on the geochemical conditions. A primary challenge for engineering field implementation is the development of non-linear geo- and physico-chemical conditions between the electrodes. These conditions result in a non-uniform electroosmotic flow and coupled chemical and mechanical processes that are heterogeneous and transient (time and space dependent).

The relatively low permeability of silt and clay soils coupled with the transient and heterogeneous geochemical conditions result in transient fluid flow and development of negative or positive pore pressure. This is a major issue for two reasons. First, changes and dissipation of excess pore pressure will induce soil deformation and limit the potential for implementation under existing structures. A successful field implementation of electrokinetic soil remediation could be, on the contrary, a feasible and effective solution in constructed areas since it does not require soil removal. Accurate evaluation of the induced deformations over time is therefore necessary though not always taken into account. Of course this factor is more relevant when engineering electroosmotic soil consolidation and dewatering or when the goal is the increase in soil strength. Moreover, soil deformation can lead to a change in the hydraulic conductivity that must be taken into account at contaminated sites. An increase in permeability would lead to a higher advective flow and thereafter to a greater influence on contaminant transport.

Second, the development of suction can cause a decrease in the soil water content and lead to development of tension cracks in the treated soil. This results in a high electrical resistivity zone, and a decrease in the transport of ions causing the slowdown and possible shutdown of the process.

Excess positive or negative pore pressures have been shown to develop under different treatment conditions. The development of excess pore water pressure or suction is the result of either different flow boundary conditions (e.g. closed anode) or non-uniform driving forces between the electrodes [12, 19–22]. Esrig's [12] electroosmotic consolidation model shows that under ideal conditions, no excess pore water pressure will generate in the case of open boundaries. This holds as long as no physico- or geochemical changes are induced between the electrodes.

In soil remediation, open fluid flow boundaries are usually adopted. The development of pore water pressure in the soil between the electrodes has been observed (e.g., cases of heavy metal extraction reported by Alshawabkeh and Acar [8], Alshawabkeh et al. [20] and Eykholt and Daniel [23]). Though different studies have focused on the non-linearity of electroosmotic flow [19–23], a comprehensive approach for natural soil seems still lacking and further testing of the transient physical and chemical changes is necessary for engineering in situ electrokinetic treatments.

The objective of this research is to improve the understanding of transient and non-linear coupled chemical and mechanical processes that occur in soil under the application of an electric field. This paper evaluates the mechanisms that govern the development of positive pore pressure or suction along the sample and their evolution over time. The importance of boundary conditions on the overall behaviour of the sample is evaluated. This could lead to a better prediction of pore pressure behaviour over time by monitoring the electrical potential drop. The efficiency of electrokinetic techniques could be improved and costs reduced, to ensure feasible and successful in situ implementation.

2 Experimental methods

The experimental setup (Fig. 1) consists of an acrylic rectangular cell of dimensions 15 cm high by 5 cm wide by 40 cm long to hold the soil sample. Two acrylic reservoirs are connected to the ends of the cell, allowing the measurement of pH and electrical conductivity of the anolyte and of the catholyte as well as facilitating addition of required conditioning agents. Two rigid and porous plastic filters are placed between the cell and the reservoirs to hold the sample and minimize soil dispersion into the electrolytes. Graphite electrodes are placed in the reservoirs to avoid direct contact with the specimen. All tests were conducted at constant electric current to control the boundary condition under constant electrolysis rates. Voltage, pore pressure and pH were monitored daily at different points along the sample (Fig. 2).

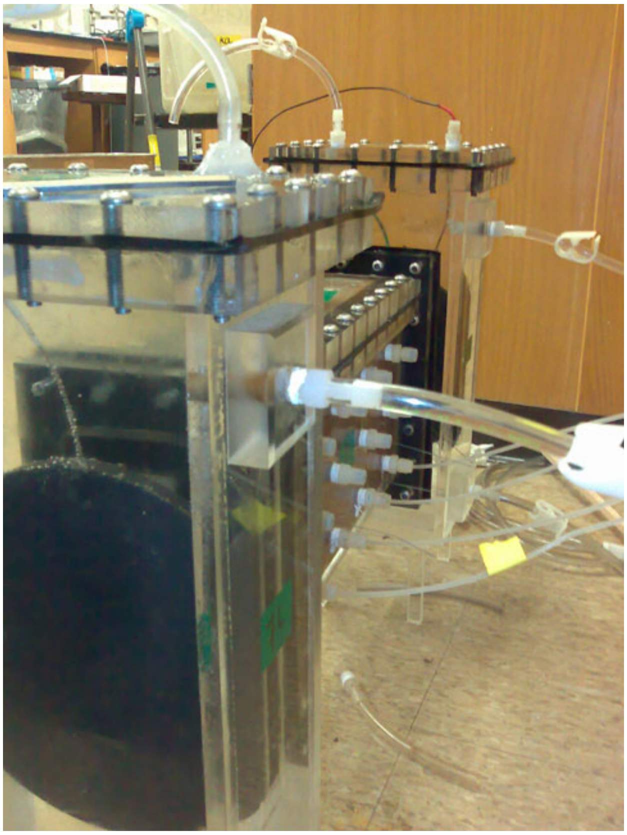


Fig. 1 Picture showing the experimental setup

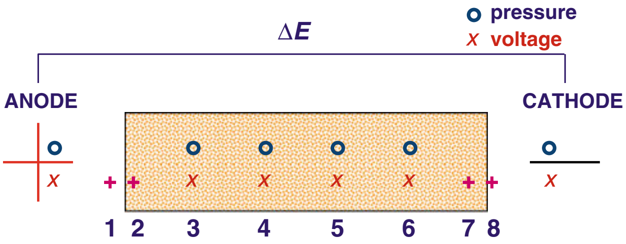


Fig. 2 Sampling ports distribution and measurement scheme

The soil used is natural silt collected from a site in New York State. The soil is classified as clayey silt with sand, having an average of 16.7% clay and 40.1% silt by weight, with specific gravity $G_s = 2.74$, liquid limit $w_L = 18$ and plasticity index $P_I = 4$. Its activity (A), conventionally defined as the ratio between the plasticity index and the percentage of particles with an equivalent diameter smaller than 2 mm, is 0.25, which indicates a soil with a low activity and a typical kaolinitic behavior. The average soil carbonate content is about 23.5% with a natural pH around neutral.

Soil samples were prepared by either compaction or consolidation directly in the cell. All the compacted specimens were prepared with water content of 15% and were compacted in 10 different layers to a relatively uniform void ratio of 0.45. To guarantee uniformity of the overall specimen, 5% under-compaction percentage was chosen [24]. To prepare the consolidated sample, dry soil was mixed with 10^{-2} M KCl solution in distilled water to water content of 1.5 times the liquid limit. The slurry was then poured in the cell and one dimensionally consolidated to reach a final void ratio equivalent to that of the compacted samples. Compacted and consolidated samples are assumed to have different pore size distribution, tortuosity and eventually hydraulic conductivity. Compacted sample structure is characterised by the presence of larger voids and a higher tortuosity. The slight pore size and structure heterogeneity result in a higher hydraulic conductivity compared to consolidated structures.

3 Results

The effects of three specific variables were assessed: (a) type of solution (b) type of amendment used in the anolyte and catholyte and (c) soil structure. Before and after the electrokinetic treatment a hydraulic gradient was imposed to the sample in order to measure prior and post-treatment average hydraulic conductivities. All electrokinetic tests were run with open flow boundaries, i.e., water was free to flow through the boundaries that were both held at a constant hydraulic head. Tests were conducted for different time durations. The tests are grouped into short term (less than 100 h processing) and long term (greater than 100 h processing) tests.

A summary of the short and long term tests is presented in Tables 1 and 2, respectively. In all tests the controlled variables were the current density and the hydraulic and chemical boundary conditions. The measured variables include electric potential drop along the sample (measured by titanium electrodes, x and +, Fig. 2), the pressure head (measured by four capillary tubes equally spaced within the sample, o) and pH in correspondence of the pressure measurement. Other measurements include pH and electrical conductivity in the reservoirs via pH and conductivity meters. In most tests, labelled CV1, the voltage configuration was measured at six locations (x). Four additional voltage measurement locations were conducted: two in the reservoirs and two in the first few millimetres of the sample (+). These allow evaluation of the potential drop at the boundaries and accurate evaluation of the potential drop along the entire length of the specimen. The boundaries were found to have the greatest influence on the overall behaviour of the sample.

Control tests were performed on sand, which has higher hydraulic conductivity and a negligible double layer compared to the silty clay soil. No net flow or changes in pore pressure were measured. The evolution of electrical conductivity and pH front advance were measured. Tests were conducted for 168 h.

The goal of the short term tests is to evaluate the peak in pore pressure that was regularly observed in the soil within the first about 30 h of treatment. All tests were run at a controlled constant current ranging from 10 to 40 mA, equivalent to a current density of 0.13–0.52 mA/cm^2. The excess pore pressure was measured at constant time intervals. The voltage was measured at 6 different locations within the sample (CV1). To assure homogeneity in the results all tests were performed with the same electrolytic solution and sample preparation. Anolyte and catholyte were composed of a 10^{-2} M KCl solution in distilled water. The same solution was used to prepare the soil that was compacted directly in the cell.

The goal of the long term tests is to investigate the evolution of pore pressure across the sample over time

Table 1 A summary of testing conditions for the short term tests

Soil type	Soil preparation	Name	I (mA)	j (mA/cm^2)	Testing time (h)	Solution composition	Notes
Silt	Compacted	S10-1	10	0.13	76	10^{-2} KCl	CV1
		S20-1	20	0.26	28	10^{-2} KCl	CV1
		S20-2	20	0.26	28	10^{-2} KCl	CV1
		S25-1	25	0.33	28	10^{-2} KCl	CV1
		S30-1	30	0.39	83	10^{-2} KCl	CV1
		S30-2	30	0.39	24	10^{-2} KCl	CV1
		S40-1	40	0.52	32	10^{-2} KCl	CV1
		S40-2	40	0.52	92	10^{-2} KCl	CV1

Table 2 A summary of testing conditions for the long term tests

Soil type	Soil preparation	Name	I (mA)	j (mA/cm^2)	Testing time (h)	Solution composition	Notes
Sand		CONTROL_1	10	0.13	168	10^{-2} KCl	CV1
		CONTROL_2	10	0.13	278	10^{-2} KCl	CV1
Silt	Compacted	LCH-1	10	0.13	941	10^{-2} KCl	CV1
		LCH-2	10	0.13	334	10^{-2} KCl	
		LCL	10	0.13	334	0.5×10^{-2} KCl	
		LCD	10	0.13	334	DI	
		LCHC	38	0.50	338	10^{-2} KCl	CV1-CONDITIONED Anode: NaOH Cathode: HNO_3
	Consolidated	LKH-1	10	0.13	314	10^{-2} KCl	
		LKH-2	10	0.13	339	10^{-2} KCl	

under different boundary conditions. All tests were run under constant controlled current having an intensity of 10 mA and a current density of 0.13 mA/cm^2. Different soil structure, pore fluid chemistry and conditioning agents were considered. To assess the effect of soil structure, compacted and consolidated specimens were tested. Three different solutions were used: distilled water, 0.5×10^{-2} M KCl and 10^{-2} M KCl solution in distilled water. The conditioned tests were performed on compacted specimens prepared with a solution 10^{-2} M KCl. Sodium hydroxide (NaOH) was added to the anolyte and nitric acid (HNO_3) to the catholyte to maintain neutral pH in both the reservoirs. The addition of chemicals at the electrolyte also increased the ionic strength of the solutions. Transport of higher ionic strength solution across the soil causes a decrease in the soil particles diffuse double layer thickness and a decrease in the electroosmotic flow.

4 Short term tests

The first test performed (LCH-1) showed an immediate change in pore pressure. After an initial decrease, pore pressure increased across the sample reaching a peak within the first 30 h, but subsequently decreased until negative pressure started to develop. The most relevant and unexpected evidence was that the change in pore pressure occurred instantaneously after the current was applied.

The total hydraulic and electroosmotic flow is expressed as:

$$q_e = k_e i_e + k_h i_h.$$

The hydraulic head is held constant at the boundaries. Net fluid flow across the sample will be induced due only to electroosmosis. Assuming a constant k_e, if the potential drop is linear, constant flow develops and no change in pore pressure takes place under homogeneous conditions and freely draining boundaries.

One possibility to explain the instantaneous change in pore pressure is that the assumption of an initial constant k_e is not valid, possibly because of lack of homogeneity of the samples prepared by compaction. However, subsequent testing on consolidated samples (LKH-1, LKH-2) having a homogenous structure showed the same behaviour. Moreover, though local differences in pore pressure evolution over time were observed, the average behaviour was similar for all tests.

Electric current will instantaneously induce electrolysis and chemical change. These will influence the electroosmotic permeability coefficient, which depends on the soil surface potential, pore fluid chemistry and pH. A change in the value of k_e would lead to the development of a non-uniform flow and to changes in pore pressure. However, this explanation is unlikely to justify the immediate response and the behaviour in the short duration experiments. The change in pressure occurs almost instantaneously, prior to any significant change in geochemistry due to electrolysis, especially considering that low current densities ($j = 0.13$ mA/cm^2) are applied through a large volume of water in the reservoirs (more than 5 L of solution). At the same time, a linear electrical potential distribution is expected to develop along the sample, at least at the start of the process. All tests showed a linear potential drop within the specimen for the first few hours, though pore water pressure was continuously changing.

The pressure build-up over the first 30 h could indicate that instantaneous flow will not occur in soils under electrical gradients until a specific mobilizing value is reached. Once that mobilizing pressure value is reached, electroosmotic flow will initiate. On the other hand, pressure build-up could be caused by a structural limit of the soil to water flow. Assuming that it is due to structure, its low hydraulic permeability and tortuosity, a minimum value, q_m, is required to induce flow. In absence of hydraulic gradients, the flow will be due to electroosmosis and its value, q_e, will increase with the increase in voltage gradient across the sample. If the electroosmotic flow induced by the applied electric current is larger than q_m, then effluent flow will be measured. Pore pressure build-up across the sample will develop until flow occurs. After that, the pressure will dissipate as the driving force required for flow will be lower once the flow is initiated. This is consistent with the fact that frictional resistance for flow along the particles is lower under flow than the one under no flow conditions. The concept is also supported by the results, showing that the anodic boundary potential drop will control the magnitude of the influent flow. The excess pressure will dissipate over time because frictional resistance for flow immediately decreases after flow and because deformation may start to occur. Over time, geochemical changes will occur as a result of electrolysis and transport. A different pore pressure may develop depending on the outcome of the changes in soil geochemistry.

A set of short term tests were designed to investigate the trend in pore pressure build-up. A consistent behaviour was observed, a peak in pore pressure was measured across the soil in all tests within the first 30 h of treatment. The maximum excess pore pressure measured at a single port and the average of the measurements at the four ports are plotted (Fig. 3) as a function of current density for all the compacted samples with 10^{-2} M KCl pore fluid. The relationship appears to be linear within this range ($I = 10$–40 mA; $j = 0.13$–0.52 mA/cm^2) validating the hypothesis on the microstructure effect. Increasing the applied current will result in higher potential drop and higher mobilized flow, q_e. However, the immediate flow that the soil is able

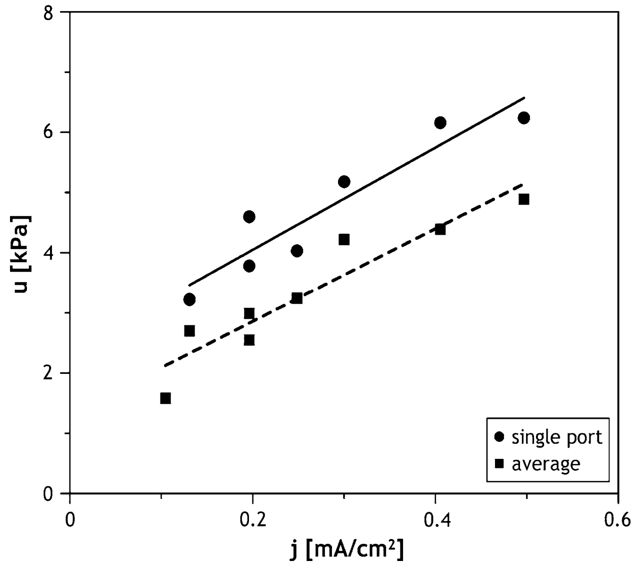


Fig. 3 Average and maximum pore pressure versus current density

to undergo, q_m, is the same for the sample under different gradients. Therefore, a higher difference between q_e and q_m will correspond to a higher pressure build-up. The pressure build-up should be linearly related to the ratio of q_e to q_m.

5 Long term tests

Similar trends in average pore pressure distribution and the total voltage drop over time were observed in all non conditioned tests. The total potential drop, presented in Fig. 4 for tests LCH-1, LKH-1 and LCD, shows a slight decrease before increasing to a peak value and subsequently stabilizing to steady state values. After ten days, an increase in the potential drop was observed near the cathode due to precipitation and deposition of salts in the basic environment. The tests that did not show this increase were performed with distilled water (LCD, Fig. 4) and with conditioned electrolyte (LCHC).

Figure 7a, b and 7c (solid line) show the average pore pressure development over time for tests LCH-1, LKH-1 and LCD, respectively. The average pore pressure instantaneously decreases and then increases to a peak value within the first 30 h. Excess pore pressure then dissipates and suction develops along the entire sample at a relatively constant average rate. The conditioned test (LCHC, Fig. 7d) showed a similar behaviour, with a peak in average pore pressure. The pressure then dissipated to a zero value. Within the last 2 days of treatment (300–350 h) the average pore pressure was −2 kPa, although the electrical conductivity of the cathodic reservoir was more than double that of the anodic reservoir ($E.C_C = 170$ S/cm compared to $E.C_A = 70$ S/cm). This indicates that suction is more likely to develop than positive pressure.

Pore pressure distribution along the sample is presented in Figs. 5 and 6 with voltage drop and pore pressure profiles for the test LCL. Although the potential drop can be considered to be linear along the entire length of the specimen, high non-linearity can develop at the boundaries, at least for the first few hours.

As highlighted by Fig. 5, as soon as the electric current is applied, a sharp potential drop develops at the anodic boundary (soil–electrolyte interface). This potential drop increases for about 3 days until equilibrium is reached at the interface. On the contrary, at the cathodic boundary the potential drop at the electrolyte–soil interface is initially very small, but increases over time to a value higher than the

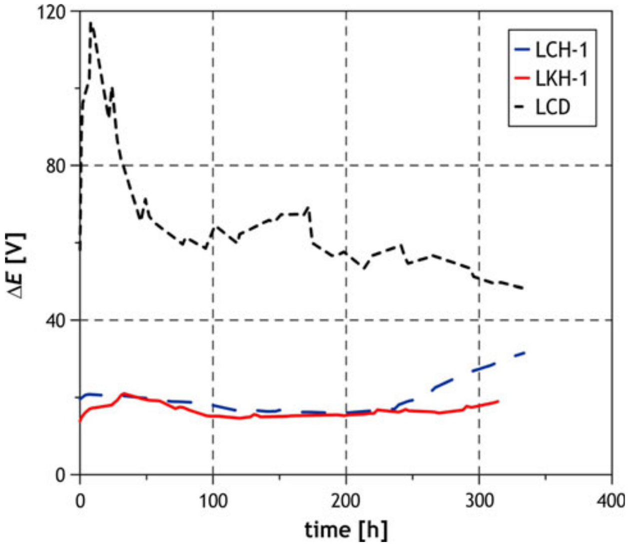


Fig. 4 Potential drop over time, tests: LCH-1, LKH-1, LCD

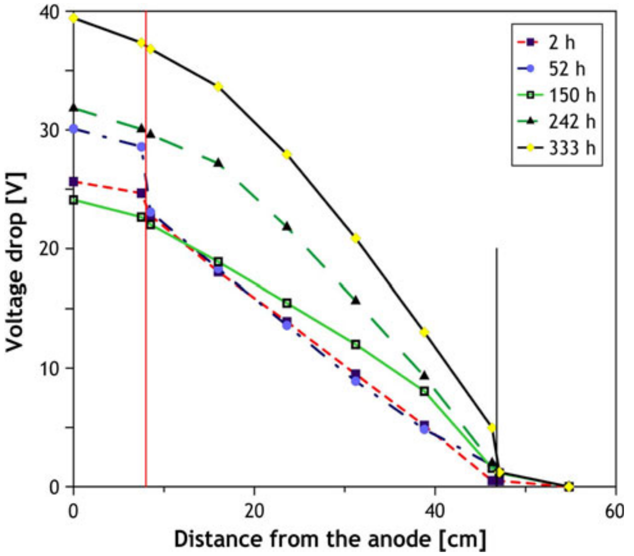


Fig. 5 Voltage drop profile for test LCL (solution 0.5×10^{-2} KCl)

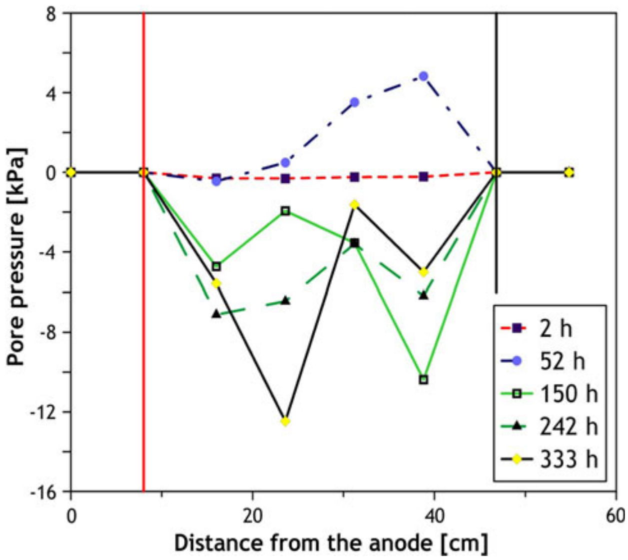


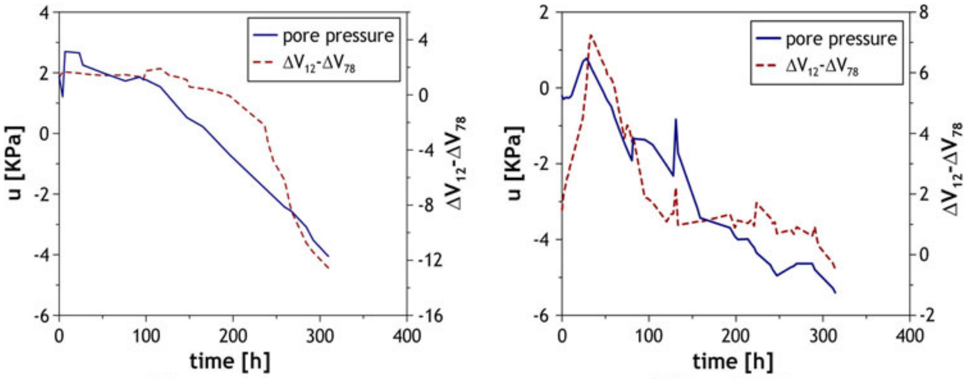
Fig. 6 Pore pressure profiles corresponding to the voltage drops presented in Fig. 5

average gradient across the specimen. The increase in potential drop at the cathode interface then propagates towards the anode with an overall increase in the total potential drop over time. This is due to the geochemical effects and progress of the basic front moving from the cathode towards the anode. After 10 days a very sharp potential drop develops within the last few millimetres of the sample creating strong non-linearity in the potential distribution.

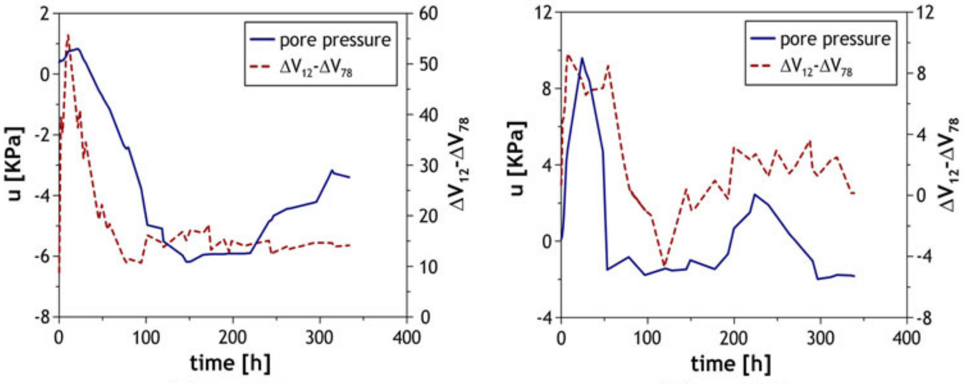
It could be inferred that initially a relatively high potential gradient develops at the anode electrolyte–soil interface causing a strong discontinuity within the soil specimen. Over time and as the conditions equilibrate at the anode interface, the cathodic boundary starts to develop the highest potential gradient. The impact of the boundary electrolyte–soil interface is apparent in Fig. 5. For example, a potential drop of 5.59 V develops after 52 h in the first 5 mm of the sample in Test LCL. The total potential drop within the sample at the same time is of 36.35 V, indicating that anodic boundary represents more than 15% of the total potential drop. With an electric gradient of 11.2 V/cm, which is nearly twenty times higher than the average gradient along the sample (0.6 V/cm). This explains the changes in pore pressure when the potential distribution within the sample is linear (Fig. 5).

The fundamental role played by the electrolyte–soil interface is apparent when comparing the average pore pressure and the electric potential difference at the two boundaries [$\Delta V_{12} - \Delta V_{78}$] (Fig. 7). This explains the immediate development of excess pore pressure in the soil. Pore water pressure is ruled by flow continuity and thus by the difference between the influent and effluent flow rates.

Fig. 7 Boundaries potential drops difference ($\Delta V_{12} - \Delta V_{78}$) and pore pressure over time: **a** compacted (solution 10^{-2} KCl), **b** consolidated (solution 10^{-2} KCl), **c** compacted (distilled water), **d** conditioned (NaOH anode, HNO_3 cathode) samples. Where ΔV_{12} and ΔV_{78} refer to the voltage difference measured between probes 1 and 2 (anode interface); and between probes 7 and 8 (cathode interface), respectively (see Fig. 2)



(a) Test LCH-1 **(b)** Test LKH-1



(c) Test LCD **(d)** Test LCHC

The influent flow rate is governed by the potential drop at the anodic boundary, ΔV_{12}; and the effluent flow rate is governed by the cathodic potential drop, ΔV_{78}. Let q_i and q_o be the influent and effluent flow rates, respectively, with $q_i = k_e * \Delta V_{12}/L_i$ and $q_o = k_e * \Delta V_{78}/L_i$, where $L = L_i$ is the distance between the voltage probes. An assumption of a constant k_e results in $q_i - q_o = k_e*(\Delta V_{12} - \Delta V_{78})/L$. If $\Delta V_{12} > \Delta V_{78}$ then the influent flow rate is greater than the effluent one ($q_i > q_o$), causing an increase in pore pressure. In contrast, $\Delta V_{12} < \Delta V_{78}$ corresponds to $q_i < q_o$ causing the pore pressure to decrease. The similarity and consistency of this behaviour was observed in all tests: compacted and consolidated structures (Fig. 7a, b), different chemistry of the solution (Fig. 7c), and addition of conditioning agents (Fig. 7d).

It is apparent that the anodic boundary potential drop, ΔV_{12}, is playing a major role in the overall pore pressure evolution over time. It is developing the highest values, ruling the influent flow and thus governing the average pore pressure distribution. At the beginning of the treatment ΔV_{12} tends to increase, causing a higher influent flow rate and development of excess pore pressure. The sample will be saturated and volume change will occur. On the other hand, as the electrolyte–soil interface reaches equilibrium, ΔV_{12} decreases to a small value, only minimal electroosmostic flow will seep into the specimen even though boundaries are open. Water flow in the specimen will be ruled by the local potential drop, which in general will be higher starting from the cathode. A higher flow will then be mobilised along the sample compared to that entering the specimen. Pore pressure will start to decrease and possibly cause formation of tension cracks. At later stages of processing, the cathodic boundary will experience the highest potential drop. Although this should cause higher exiting flow, the precipitation of salts in this region significantly clogs soil and drastically reduces the flow.

The chemical changes that are induced by the prolonged treatment and the precipitation of salts and calcite in the alkaline environment influence the pores' size and lead to a decrease in hydraulic conductivity. The lower hydraulic conductivity of the cathodic boundary has been shown by post-treatment permeability measurements. An interesting behaviour is noted with the hydraulic conductivity measurements.

Falling head conductivity tests were performed in opposite directions. Flow was induced from the anode to the cathode by keeping a constant head at the cathodic reservoir and a falling head at the anode by means of a vertical pipe tube. The same test was then performed in the other direction. All tests showed a value of the hydraulic conductivity coefficient of at least one order of magnitude lower if flow is induced from the cathode to the anode than vice versa. The direction of the flow was inverted several times and the same difference in the hydraulic conductivity was found. This does not mean that the permeability of the overall sample is different when measured along one direction or the other, because the sample becomes heterogeneous with induced physical changes (volume change) and possibly residual pressure. However, the difference can be explained by analyzing the configuration of the falling head permeability test. The value of the hydraulic conductivity is derived by the falling head measure, without accounting for the effluent flow rate. This measure is correct in the case of a homogenous saturated sample, but not in the case of a sample previously subjected to electrokinetic treatment. When flow is induced from the anode to the cathode, water starts to flow into the sample at a rate that depends on the hydraulic permeability of the soil near the anode and, since the soil is no longer fully saturated, the flow will cause changes in the soil water content, where there is a demand for water due to suction build-up. On the other hand, when flow is induced from the cathode to the anode, the governing hydraulic permeability will be that of the cathodic boundary where changes in the soil structure have occurred. The permeability of the section close to the cathode will be smaller than the rest of the sample, causing a lower apparent hydraulic conductivity of the soil. The different structure and stiffness of the last centimetre of soil after 300 h of treatment is also evident from visual observations when the soil is extracted from the cell at the end of the treatment.

Evolution over time of the average pore pressure has been shown to be ruled by the difference between the sample's initial and final potential drops $[\Delta V_{12} - \Delta V_{78}]$. The same reasoning applies locally when considering a single pressure port. At a point, pore pressure is ruled by the local non-linearity in the electric field, and it will evolve as the difference between the potential drop entering and that exiting the considered point. An example is presented in Fig. 8 where the elevation head measured at port 5 and $[\Delta V_{45} - \Delta V_{56}]$ are plotted against time.

This discussion is under the simplifying assumption of a constant k_e. Although this is not the case, as discussed by Alshawabkeh et al. [20], the coupled effect of non-linear geochemical and physical conditions will govern the overall behaviour. Other processes will influence the non-linear pore pressure distribution, especially over time and with the modifications induced by the geochemical reactions. Electrokinetic treatments have been proved to modify the microstructure of porous materials as soil and concrete, and to modify the hydraulic and mechanical behaviour of soil [25]. However, on the basis of the amount of data collected, it appears that the most quantitatively relevant role governing the process is played by the non-linearity in the potential drop distribution, with the major role played by the boundary potential drops.

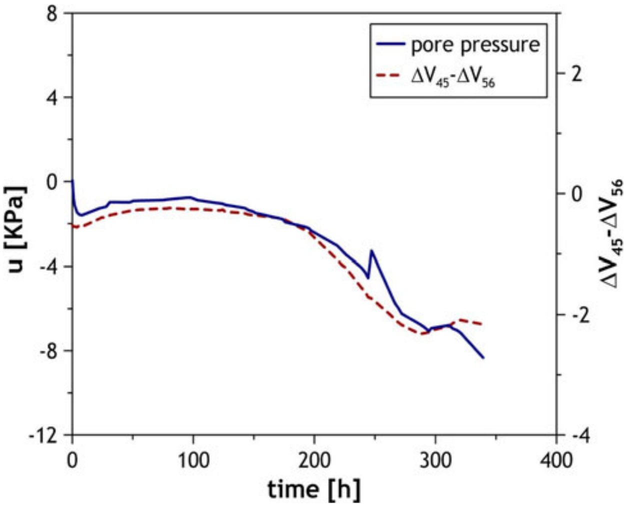


Fig. 8 Potential drops difference ($\Delta V_{45} - \Delta V_{56}$) and pore pressure (5) against time for test LKH-2. Where DV_{45} and DV_{56} refer to the voltage difference measured between probes 4 and 5 and between probes 5 and 6, respectively

6 Conclusions

An experimental program aimed at clarifying the behaviour of pore pressure in soils subjected to electrokinetic treatment was conducted. A peak in pore pressure that is linearly related to the electric current density is observed within the first 30 h for all tests. Pore pressure evolution over time is governed by the local non-linearity in the electric field. In particular, the overall average pore pressure is ruled by the difference between the potential drops that develop within a few millimetres at the soil anodic and cathodic boundaries (electrolyte–soil interface). The sharp potential gradients that develop at the interface between soil and electrolyte govern the influent and effluent flow rates. An accurate measure of the potential drop at the boundaries could lead to better prediction of pore pressure evolution over time.

Better understanding of pore pressure evolution would lead to a better engineering of in situ electrokinetic treatments since non-uniform flow can cause significant geotechnical changes, possibly leading to unsuccessful treatment. The knowledge of the soil hydraulic and mechanical behaviour could allow calculation of the possible deformations. The control of boundary conditions could then become a powerful tool to predict and regulate pore pressure along the length of the treatment. Development of high boundary gradients could be avoided, resulting in reduced power consumption, improved efficiency and lower costs.

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