

Influence of electroosmotic treatment on the hydro-mechanical behaviour of clayey silts: preliminary experimental results

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Abstract Preliminary results of an investigation focused on the influence of electrokinetic treatment on the mechanical and hydraulic behaviour of clayey soils are presented. The experimental programme aims at providing a contribution to the sustainability of contaminant extraction or containment via electroosmosis. Changes in the hydraulic and mechanical properties of two illitic clayey soils, subjected to a DC electric field, were investigated. Samples of the two soils were subjected to electrokinetic filtration, for different periods of time, and under different constant loads. Afterwards, they were tested under one-dimensional compression to detect changes in stiffness and hydraulic conductivity due to the electrical treatment. After the application of a DC field for a few hours, a small reversible increment in the average soil stiffness was

observed, with respect to the untreated soil, while the hydraulic conductivity was not affected substantially. Dramatic changes of the mechanical and hydraulic soil properties, correlated to changes of the soil pH, were observed following non-conditioned electrokinetic treatment with duration of the order of days.

Keywords Clayey soils · Electrokinetic treatment · Electro-hydro-mechanical coupling · Experimental investigation

1 Introduction

The experimental investigation presented is part of a wider research project aimed at providing a contribution to the sustainability of contaminant extraction and containment via electroosmosis in natural soils. The objective is to develop a theoretical and numerical model for coupled deformation and hydraulic, ionic and electrical flow processes occurring in soils undergoing electrokinetic treatment, which could be used to obtain quantitative predictions for field performance.

The development of electrokinetic processes for soil decontamination and prevention of pollutants migration from contaminated sites, starting from the 1990's [1, 2], followed previous work on the application of the technique to soil consolidation and stabilisation. Pore pressure changes caused by electroosmosis [3–8] and a broad series of other coupled processes, including ion exchange, physico-chemical adsorption and desorption, structural changes of clay aggregates, and chemical reactions in the pore water leading to insoluble precipitates binding the soil, have been suggested as possible causes of soil hardening accompanying electrokinetic treatment [9, 10]. An important

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role in the environmental efficiency of the technique is attributed nowadays to changes in soil pH, primarily due to hydrolysis reactions at the electrodes [11–19], but few systematic studies are available on the influence of pH on the mechanical behaviour of natural clays [20], to the author's knowledge. Finally, most previous studies were performed on artificial mono-mineral soil samples, as the mineralogic heterogeneity of natural soils complicates the electrochemical interpretation of the test results. In contrast, previous experimental evidence suggests that physical and chemical properties of natural soils, affecting electrokinetic treatment efficiency, can change in ways that are different from artificial soil samples; hence, in order to predict the electrochemical effects arising during in situ treatments, natural soil cores should undergo preliminary laboratory testing [21].

Starting from the last consideration, the first step of the investigation was focused on detecting the consequences of electrokinetic treatment on the mechanical and hydraulic properties of selected natural soils from a macroscopic viewpoint, more than on trying to analyse all the coupled electrochemical processes which are responsible of the soil behaviour at the microscopic level. Evolution of mechanical stiffness, hydraulic conductivity and electroosmotic permeability was investigated.

Results of both short and long term electrokinetic treatment performed in the laboratory are presented. The first procedure is of industrial interest for waste containment through so called electrokinetic fencing. Here, since contaminants do not have to be removed from the soil mass, but simply prevented from migrating in the aquifer, a DC field is applied from time to time to counteract the migration of polluting species occurring because of diffusive and advective fluxes [22]. Short duration of the treatment limits the effects of electrochemical reactions. Therefore, hydro-mechanical changes are expected to be mainly due to local desaturation processes or, possibly, to temporary direct consequences of the electrical field on the clay particle aggregates.

Long term electrokinetic treatment is of interest for actual decontamination of polluted sites. To be effective, the DC field has to be applied long enough to ensure removal of contaminant; hence, at least for a period of time sufficient to mobilise a pore volume of saturating water, if electroosmosis is the prevailing transport mechanism. In this case, pore water chemistry is strongly affected by chemical reactions. The observed hydro-mechanical effects, being related to the actual chemical changes taking place, will depend on conditioning techniques provided at the electrodes. In this respect, the non-buffered conditions implemented in the present study are of relevant importance to highlight the electrochemical effects due to the dramatic water chemistry heterogeneity expected along the

sample, and for future comparison with buffered treatments.

2 Soils investigated and sample preparation

Two natural clayey soils were studied: a clayey silt from Viadana (near Mantova) in the Po river valley, and a scaly clay from Scanzano (near Palermo). The first is a clayey silt with an average clay content of about 30.0%, and about 70.0% silt, with specific gravity, defined as the ratio between the soil particle density and the reference water density, $G_s = 2.74$, liquid limit $w_L = 0.59$ and plasticity index $PI = 0.30$. Its activity, conventionally defined as the ratio between the plasticity index and the percentage of particles with an equivalent diameter smaller than $2 \mu\text{m}$, is $A = 0.9$, which indicates a soil with typical illitic behaviour. Natural Scanzano clay is an illitic–kaolinitic strongly structured scaly clay, with a small quantity of smectite. The soil particles have specific gravity $G_s = 2.78$, liquid limit $w_L = 0.58$, plasticity index $PI = 0.30$, and activity $A = 0.88$. All the soil physical parameters were determined following standard test methods [23, 24].

The mineralogical composition may be better appreciated with reference to Fig. 1, where X-ray diffraction data for the two natural soils are compared. Both soils are rather heterogeneous, with a prevalence of illitic and kaolinitic minerals. Calcite was detected by XRD on both samples. In Fig. 2 the pore size distributions of natural samples of the two soils are reported, as determined by mercury intrusion porosimetry performed with a Carlo Erba porosimeter allowing for a maximum mercury pressure of 200 MPa [25, 26]. Pores with an equivalent entrance diameter in the range from $100 \mu\text{m}$ to $0.007 \mu\text{m}$ can be detected with this equipment. Viadana silt has a prevailing mono-modal

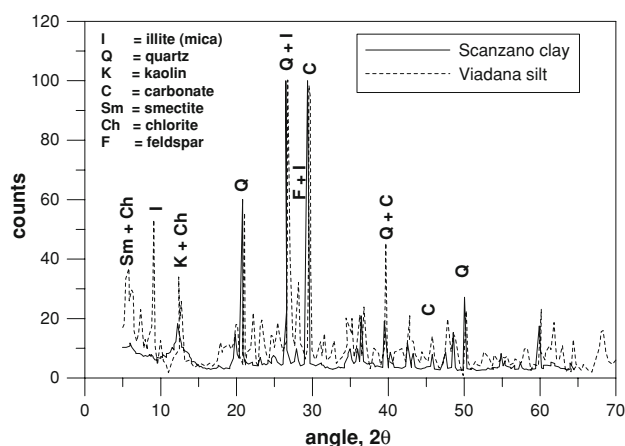


Fig. 1 X-ray diffraction analysis of the two soils investigated: Viadana silt and Scanzano clay

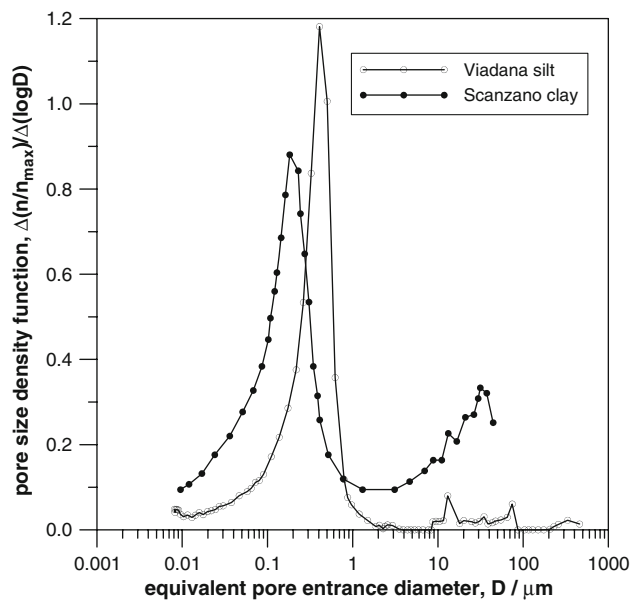


Fig. 2 Pore size density of the two natural soils: Viadana silt and Scanzano clay

distribution of pores, with a peak around an equivalent entrance diameter of 0.4 μm . Scanzano clay has a more pronounced bi-modal structure, formed by clay aggregates, with a mean micropore entrance diameter of 0.15 μm and interaggregate pore entrance diameter of about 30–40 μm .

The electro-hydro-mechanical tests were performed on samples prepared in the laboratory starting from the natural soils. Standard and repeatable procedures were adopted for each soil, in order to minimise the differences induced by different preparations. Samples of Viadana silt were prepared starting from the material passing through a 2 mm sieve, after air drying and grinding with a rubber pestle. Distilled water was sprayed over the soil and carefully mixed in order to reach a water content of $w_0 = 0.280$, defined as the ratio between water mass and soil particles mass. After a curing time of 24 h for homogenisation of the water content, the soil was dynamically compacted in layers, directly into the cells where the electro-hydro-mechanical tests were performed. The target void ratio, defined as the ratio between the volume of voids and the volume of the solid particles, was $e_0 = 0.89$. The as-compacted degree of saturation of the soil samples was $S_{r0} = 85\%$. Prior to the application of an electrical field, the samples were saturated by water flushing at increasing pressure.

Scanzano clay was also prepared starting from air dried material, ground with a rubber hammer first and with a ceramic pestle in a mortar afterwards. In order to achieve complete saturation before mounting the sample in the electrokinetic cell, a slurry at one and a half times the liquid limit of the clay was prepared. The solid particles

were mixed with a 10^{-2} M KCl solution in distilled water, and left to homogenise for 24 h. In this case, as electrokinetic treatment of duration of weeks were planned, the composition of the pore fluid was chosen so as to ensure stability of the Ag/AgCl measurement electrodes and minimise its variation in time. In this way, an accuracy of 1.2% in the measurement is assured [18]. The slurry was then poured in a cylinder with rigid lateral walls, and one dimensionally consolidated in load steps up to a vertical stress of 100 kPa. After preparation, the saturated sample had a void ratio of $e_0 = 0.95$, corresponding to a water content of $w_0 = 0.347$. The sample was then extracted and mounted in the cell for electrokinetic tests.

Short term treatments, of the order of hours, were performed on Viadana silt, while longer treatments, of the order of weeks, were performed on Scanzano clay, in order both to exploit all the equipment in parallel and to test at least two soils which share similar characteristics from the geotechnical viewpoint. Future investigation is planned to verify to what extent the two soils share similar electrochemical properties too.

3 Experimental equipment and procedures

Electrokinetic tests are usually performed in cells where neither mechanical nor hydraulic boundary conditions are usually controlled, allowing for one-dimensional electrokinetic filtration tests to be performed on laterally confined samples, but without stress control. A similar cell, provided with hydraulic boundary conditions control, designed by Musso at the Politecnico of Torino (2000), was used in the investigation. The Perspex cell comprised an anolyte reservoir, a central compartment containing the specimen (80 mm in diameter and 120 mm in length) and a catholyte reservoir. Each reservoir was made of a cylindrical body, hydraulically connected to the specimen, from which the gas generated by electrolysis escaped, without entering the sample. The anode and cathode sealed the reservoir external sides. Accurate measurement of the water volume outflow was provided at the catholyte reservoir by a differential pressure transducer. The two heads of the specimens were protected by a Whatman glass micro fibre filter in order to prevent electrophoretic transport of the soil particles towards the anode and electroosmotic erosion of the soil on the cathodic side. Due to the electrochemical restrictions for the electrode materials, a graphite anode and a stainless steel cathode were used. Measurement of the potential drop was made using nine equally spaced silver electrodes, and temperature measurement is achieved along the specimen via three thermo-couples.

The long term filtration test was performed in this cell, under controlled current density. At the end of the

electrokinetic test, the sample was extracted from the Perspex cell and cut in four slices, on which pH was measured with pH strips. Previous experience showed that these measurements are consistent with those of a more precise *Crison 507* pH meter equipped with a 52-02 electrode, specifically designed to measure pH of soils [18]. The slices were then mounted in conventional geotechnical oedometer equipment and subjected to confined one-dimensional compression tests, performed by increasing the vertical load in steps, while measuring the vertical displacement. Afterwards, the samples were unloaded following the same loading steps. At the end of the test, the final water content and the final void ratio were determined. Increasing the load in steps allows for a description of the evolution of the average one-dimensional stiffness of the samples as a function of the stress level. Readings of vertical displacement in time at constant load can be elaborated for an indirect determination of the hydraulic conductivity, also as a function of the stress level.

Two other equipments were specially designed to perform electrokinetic tests on samples already under load, with the aim of verifying to what extent the stress state may influence the electrokinetic soil properties. The cells allowed for the control of both vertical stress and electric field on laterally restrained samples (oedometer conditions). Measurement of water flux was provided on the hydraulic connections at the top and the bottom of the cell. The first electroosmotic oedometer, originally designed by Tamagnini [27] for short term treatments, used sintered bronze porous electrodes. The second cell, designed and manufactured at the Universitat Politècnica de Catalunya [28], originally conceived to perform oedometer tomographic tests (EIT cell), was in order to apply an electrical field by squared platelets of pure silver ($\text{Ag} > 99,99\%$). Filter paper was interposed between the cell bases and the soil samples to distribute the electric field and to prevent loss of solid material through the hydraulic connections. Silver thread probes were located on the cell side to control the uniformity of the electrical field. The cell allowed testing of unsaturated samples under control of suction.

All tests performed with these two devices were run with alternating controlled load steps, increasing vertical stress at null electrical potential ($\Delta\sigma_v > 0$, $E = 0$), and electrokinetic treatment at constant load ($E > 0$, $\Delta\sigma_v = 0$).

4 Short term electrokinetic treatment: experimental results

The short term electrokinetic filtration tests were performed in the two oedometer devices by imposing a constant electrical potential of about 1 V cm^{-1} under constant load at vertical stresses ranging from $\sigma_v = 20 \text{ kPa}$

to 500 kPa . Duration of the electrokinetic stages was between 30 min and 3 h. Applied voltage and duration were chosen to be comparable to those adopted in electrokinetic fencing in situ [29]. As expected, during the electrokinetic treatment no appreciable vertical displacements were detected, indicating that no relevant water pressure changes were induced throughout the sample, when free drainage at the boundaries was guaranteed.

Different filtration tests were performed at different constant electrical potential, ranging from 3 to 5 V to determine the average electroosmotic permeability. The outflow data of these stages are presented in Fig. 3 (symbols). At the beginning of the filtration tests a transient stage was observed, after which a constant outflow rate was achieved. The interpolations lines depicted in the figure describe the steady state outflow rate. If the latter is represented as a function of the total applied voltage, as in Fig. 4, the activation voltage can be determined, and was found to be 1.44 V. The electroosmotic permeability was calculated with reference to the net electrical potential, defined as the difference between the applied voltage and the activation voltage. A value of about $k_e = 0.9 \times 10^{-9} \text{ m}^2 \text{ V}^{-1} \text{ s}^{-1}$ was determined for Viadana silt. At constant electrical potential, the water volume outflow did not depend on the stress level, indicating that, for the stress levels investigated, electroosmotic permeability is independent of the void ratio, which was varying in the range $e = 0.9$ to 0.8 .

In Fig. 5 the results of one-dimensional load stages performed after electrokinetic treatment on Viadana silt are compared to similar data for the natural soil. The figure reports the axial (vertical) strain determined from the displacement readings as a function of the applied stress. The comparison highlights that the electrokinetic treatment induces an initial increment of the average stiffness of the soil. The treated soil experiences a slightly smaller axial strain with respect to the untreated sample under the same

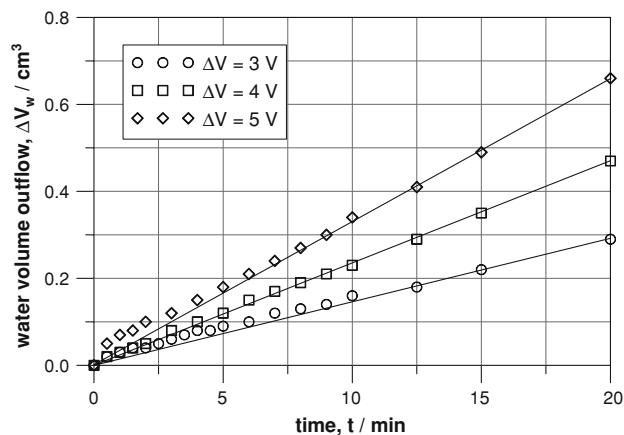


Fig. 3 Short term electrokinetic filtration test on Viadana silt: outflow data

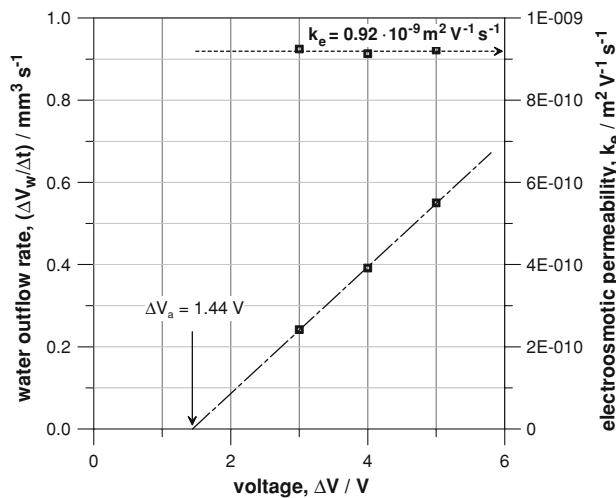


Fig. 4 Viadana silt: determination of electroosmotic permeability

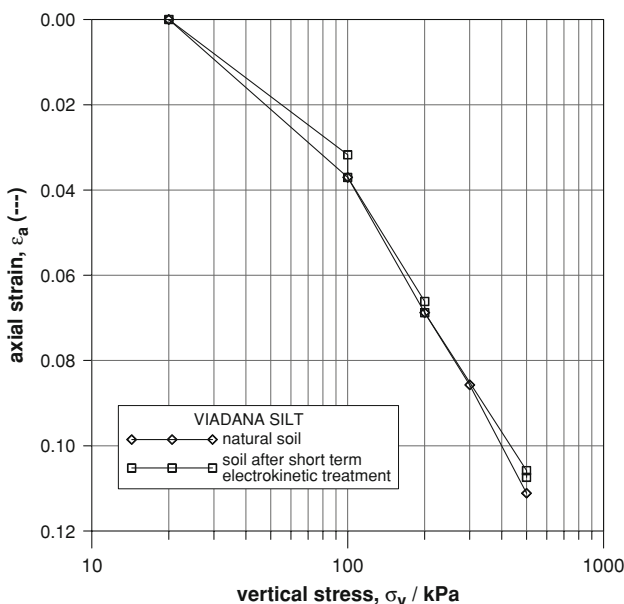


Fig. 5 Results of one-dimensional compression test performed on Viadana silt after short term electrokinetic treatment

stress increment. The effect is quantitatively more pronounced at low stress levels but systematic. Nevertheless, when the treated sample was left under constant load for at least 24 h, it almost recovered the same total strain as the natural one, following a small abrupt volume reduction observed 5–10 h after the application of the load increment. Systematic repeatability of the observation at increasing stress level suggests that reversible processes are taking place during short term electrokinetic treatments.

At least in part, the observed behaviour is due to gas production associated with water electrolysis. In fact oxygen generated at the anode cannot escape easily from the sample, as it is entrapped by the water flowing into the

sample in the opposite direction. When the electric field is stopped, and a load increment is provided, the direction of the water flow is reversed and the entrapped air may eventually flow out from the sample with the aid of water flow. If the sample, or at least a part of it, partially desaturates due to gas generation, capillary forces may arise, which may be responsible for an increase in the soil stiffness. As the gas escapes, full saturation is recovered and the temporary increase in stiffness is lost. Nevertheless, in the light of the results presented in the next paragraph, the electrochemical processes undergone by the soil, especially local variation of pH occurring close to the electrodes during the electrokinetic treatment, may contribute to a temporary increase in average stiffness. When the soil pH is re-equilibrated during the loading stages at null electrical field, the samples may recover the natural untreated soil behaviour.

5 Long term electrokinetic treatment: experimental results

5.1 Electrokinetic filtration test

A sample of Scanzano clay, mounted into the electrokinetic cell after consolidation in saturated conditions, was subjected to electrokinetic filtration continuously for 15 days, under a constant current density of $j_c = 8 \text{ A m}^{-2}$. Current density control was preferred to voltage control, to supply constant electrical charge rate throughout the whole test. No conditioning techniques were adopted in the test, to highlight all the possible hydro-mechanical effects of long term application of electrical field to the tested soil.

Time evolution of the average potential drop between the two side probes, close to the anode and to the cathode respectively, is reported in Fig. 6. The data show that the average potential drop remained almost constant and equal

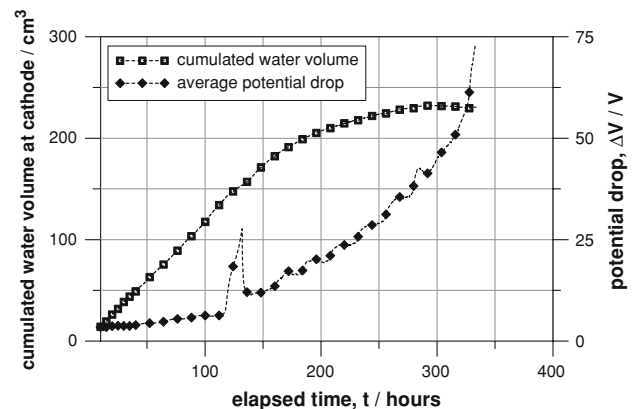


Fig. 6 Long term electrokinetic filtration test on Scanzano clay: cumulated outflow and mean potential drop

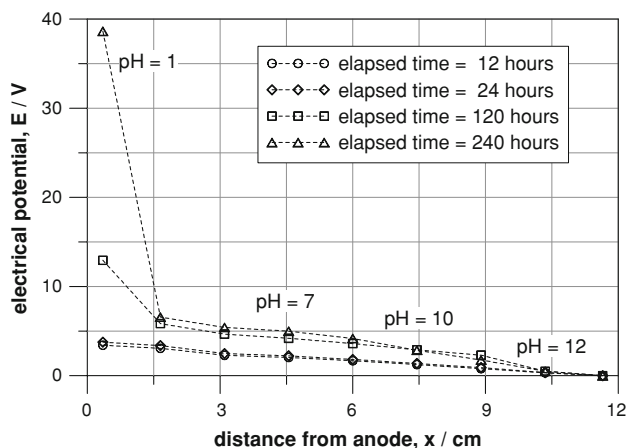


Fig. 7 Long term electrokinetic filtration test on Scanzano clay: isochrones of the electrical potential along the sample axis

to $E = 3.5$ V for nearly two days, after which the current density could be maintained only with an increasing power supply. The data for cumulated water volume show that a constant water flow rate is observed as long as the potential gradient keeps constant. The following increase in the average potential drop is accompanied by a progressive reduction of the water flow rate, which eventually stops after about 12 days. In Fig. 7 isochrones of the electrical potential distribution are presented, together with the pH values measured at the end of the test. For the first two days, the potential gradient is almost constant along the sample. Starting from the third day, a dramatically increasing potential drop is observed between the first and the second probe, while in the rest of the sample the potential pattern remains linear. This evidence confirms that a noticeable drop of the soil conductivity is associated with the transition between acidic and basic conditions [16]. The pH measurements performed at the end of the filtration test confirm that the acidic front stopped rapidly. The potential drop gradient was accompanied by a strong pH gradient, with a value around $\text{pH} = 1$ close to the anode, increasing significantly already at a distance of 3 cm, where a value of $\text{pH} = 7$ was measured. Moving towards the cathode, the pH further increases up to a pH value of 13, ending above the typical value for natural untreated samples, which is slightly higher than 7. Most literature reports that transition between acidic and basic conditions occurs closer to the cathode, in principle because of the higher mobility of H^+ ions. Nevertheless, a high gradient of the soil pH close to the anode was detected in some previous laboratory investigations of a different natural clay [18, 30], and similar evidence was found in pilot tests performed in a natural silty clay deposit [21].

Time evolution of the average electroosmotic permeability is presented in Fig. 8. A value of $k_e = 2 \times 10^{-9} \text{ m}^2 \text{ V}^{-1} \text{ s}^{-1}$ was found for Scanzano clay until the water flow rate

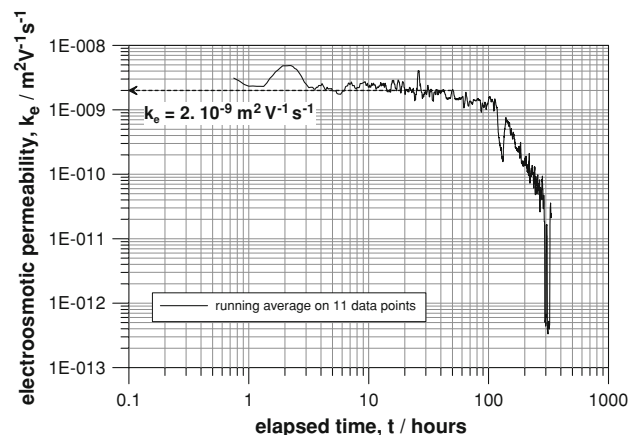


Fig. 8 Long term electrokinetic filtration test on Scanzano clay: time evolution of the average electroosmotic permeability

remained constant. When the potential gradient begins to increase near the anode, a concomitant reduction in the average electroosmotic permeability, measured on the whole cell length, is observed, which drops by three orders of magnitude in 15 days. Assuming constant water flux along the axis of the sample, the average electroosmotic permeability decrease is related to the marked electrical gradient developed close to the anode, while on the cathodic side the apparent electroosmotic permeability does not change considerably, as already reported [30]. Since the effective electroosmotic permeability depends on the physical and chemical interaction between the clay particles and the pore fluid, continuity of the water flow, ensured by controlling the hydraulic boundary conditions, implies an effective opposite Darcian flow. Hence, water pressure gradients, changing the effective stress state of the sample, must have developed.

When the soil sample was extracted from the electrokinetic cell, fractures were detected in the first portion of the sample close to the anolyte. The opening of cracks close to the anode was already reported as a problematic drawback in electrokinetic applications [22], and was justified as a consequence of desiccation. In the present experimental test, cracks appeared under controlled hydraulic boundary conditions, in principle assuring saturated conditions. High pH gradients, in turn promoting high water pressure gradients and high effective stress changes, must have contributed to crack formation.

5.2 Mechanical and hydraulic behaviour

After the electrokinetic filtration test, the soil was extracted from the cell and cut into four slices 30 mm thick each. The slices were sampled and mounted into conventional oedometer equipments, where one-dimensional compression tests up to a final vertical stress of 1600 kPa were performed. The latter tests allow for analysing the

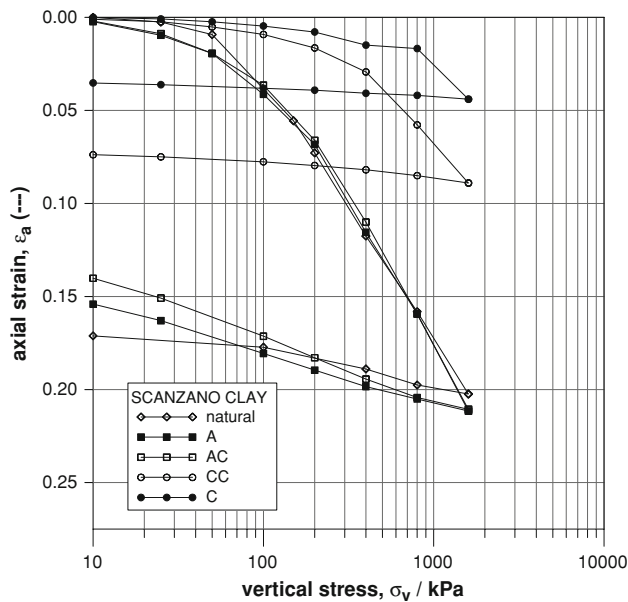


Fig. 9 Results of one-dimensional compression test performed on Scanzano clay after long term electrokinetic treatment

hydraulic and mechanical consequences of the previous electrical treatment along the original sample axis, from the anodic to the cathodic side.

The results of the compression tests are shown in Fig. 9, compared to analogous data for an untreated sample. On the anodic side, the global stiffness of the sample is not affected significantly, as the three curves for the untreated sample (natural), the first sample (A: 0–30 mm from anolyte) and the second (AC: 30–60 mm from anolyte) do not differ much all over the stress range investigated. In contrast, a strong increase in stiffness is observed for the samples cut from the side closer to the cathode (CC: 60–90 mm from anolyte and C: 90–120 mm from anolyte), whose vertical strain under the same final maximum stress was reduced, respectively, by a factor of two and a factor of four with respect to the natural sample. The apparent consistency of the samples increased strongly going from the anode side (A) to the cathode side (C). The sample (A) still showed some open fractures after the one-dimensional compression test, in spite of the high stress previously experienced.

A quantitative comparison between the samples stiffness, as a function of void ratio, is shown in Fig. 10, where the final average pH values of the different samples are also indicated. The values of the oedometer modulus are reported as a function of the void ratio corresponding to the value of vertical stress at the end of each load step. The oedometer modulus is a common measure of the current soil stiffness and is defined as the ratio between a vertical stress increment and the corresponding strain increment, in laterally confined one-dimensional compression test. It is

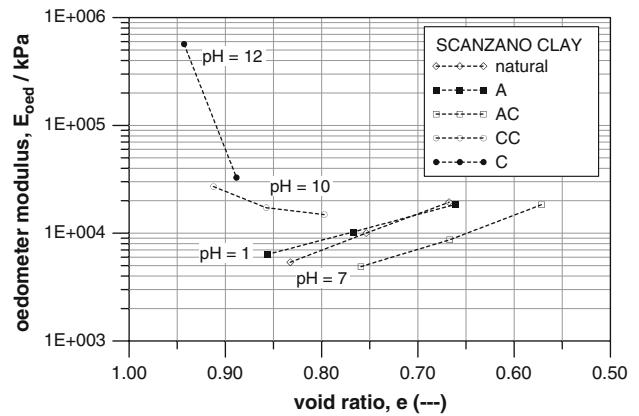


Fig. 10 Stiffness of Scanzano clay samples as a function of void ratio and final pH values

well known that the oedometer modulus for a non-cemented soil increases with its consistency as the void ratio decreases. In this case, this holds true for the natural sample, as expected, and for the samples on the anodic side. In contrast, in high pH environment the oedometer modulus may vary by nearly two orders of magnitude and it decreases, slightly for sample CC and more dramatically for sample C, with increasing stress. A stiffness decrease with increasing stress may be typically observed on cemented soils, when mechanical destructuration of the original cemented matrix accompanies irreversible strain upon loading. The results seem to suggest that precipitation of calcite may have occurred on the cathodic side, at increasing pH, as previous experimental evidence suggests [30]. Calcite bridges between the clayey soil aggregates may be responsible of the apparent cementation effect, which is lost upon mechanical destructuration. The interpretation is substantiated by measurements on the soil samples, performed following the standard code of practice [31] after electrokinetic filtration, revealing that calcite content (mass ratio referred to solid mass) varied from a minimum of 1.4% close to the anodic side to a maximum of 18% close to the cathode, compared to the natural untreated soil carbonate content which is around 15%.

In Fig. 11 data for hydraulic conductivity are presented. When a saturated soil sample is loaded, volume changes do not develop instantaneously, as an equal amount of water volume must be exchanged through the soil sample boundaries. The volume change rate is thus almost completely governed by the hydraulic conductivity of the soil sample. Hence, following a common practice in soil mechanics, hydraulic conductivity was determined based on the time evolution of measured vertical displacement following a stress increment. This is a particularly effective procedure for clayey soils, for which direct determination of hydraulic conductivity may be very costly otherwise. The results are presented in Fig. 11 as a function of void

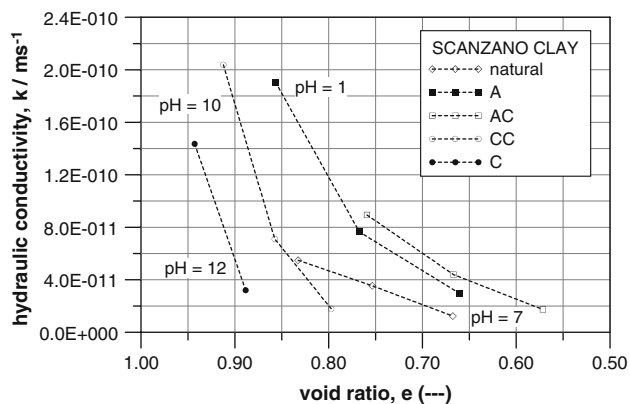


Fig. 11 Hydraulic conductivity of Scanzano clay samples as a function of void ratio and final pH values

ratio, which is usually the most relevant state parameter for hydraulic conductivity of soils. As expected, the hydraulic conductivity of all samples decreases with their void ratio, but the variations are much less pronounced for the samples at a pH of about 7, i.e. for the natural sample and the sample (AC). The relative differences between the hydraulic conductivities of the different samples are much less marked than the differences recorded for the corresponding stiffness values.

For the samples (CC) and (C) a higher hydraulic conductivity is observed at low stress, rapidly decreasing with increasing stress. The evidence is consistent with the hypothesis that calcite bridges may provide a cementation effect of the clay aggregates temporarily freezing the pore structure. The volume reduction following destructurement of the interaggregate structure reduces the mean pore size and thus the hydraulic conductivity of the samples. The higher hydraulic conductivity of the acidic sample at the beginning of the test may be probably attributed, at this stage, to the presence of open fractures, providing preferential paths for water flow. At $e = 0.75$ the hydraulic conductivity of samples (A) and (AC) compare well, although they are still slightly higher than the one of the natural sample at the same void ratio. Nevertheless, whether the sensitivity of the hydraulic conductivity of sample (A) to void ratio comes as a direct consequence of the low pH itself, or indirectly from the presence of the small fractures opened in the low pH environment, is an open question yet. Further investigation on this aspect is needed in any case, as cracking would pose severe limitations to the durability of electrokinetic barriers [22, 32].

6 Preliminary conclusions and future investigation

In the study of electrokinetic treatment for fine grained soil remediation or for enhancing the performance of

contaminant barriers, increasing knowledge of the changes in the hydro-mechanical properties of the treated soils may help in rationalising the design and in evaluating its environmental sustainability. To provide a contribution in this direction, a specific experimental programme was planned to investigate the coupled electro-hydro-mechanical behaviour of two natural illitic clayey soils. The equipments developed to run the tests and the first results of the experimental investigation were presented, which provide some useful indications on the consequences of electrokinetic treatments on hydraulic conductivity and mechanical stiffness of the treated soils.

Electrokinetic filtration lasting no more than a few hours, of interest for electrokinetic fencing, did not induce permanent modifications to the soil skeleton structure. Hydraulic conductivity and mechanical stiffness of the treated samples do not differ much from those of the natural untreated soil. The experimental results suggested that for short term treatments non-homogeneous evolution of the pore fluids pressures may be the key factor in the overall hydro-mechanical response of the soil. The effects of gas development close to the electrodes and of its dissolution in water, transport and flow through the soil, and of the influence of pore water pressure regime on the possible development of partial saturation in some parts of the treated soil needs further investigation. Besides, experimental tests are needed to enhance the knowledge of the electro-hydro-mechanical response of soils in unsaturated conditions, as few data are available at present. The need comes both from the consideration that an initially saturated soil might desaturate during electrokinetic treatment and from the possibility that the adoption of electrokinetic techniques might be suggested for superficial unsaturated soils over the ground water table.

The behaviour of the clayey soils analysed was substantially altered during and following prolonged electrokinetic filtration, of interest for soil remediation. As for the mechanical aspects, cracking on the anodic side occurred, although stiffness remained comparable to that of the untreated sample. On the cathodic side, a dramatic increase in the soil stiffness was observed. The electrical field seems to promote an overall behaviour sharing typical characteristics of cemented soils. Increasing the stress level induces mechanical destructurement, eventually overcoming the initial differences. Hydraulic conductivity of the cathodic samples was found to be always higher than that of the natural soil. This aspect requires deeper investigation and should be carefully taken into account in the design of electrokinetic barriers. The hydraulic conductivity of the anodic samples was also higher than that of the natural soil. The effects of cracking, pH, and eventual changes in soil aggregate structure should be investigated in the future.

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References

- Acar YB, Alshawabkeh AN (1993) *Environ Sci Technol* 27:2638
- Virkutyte J, Sillanpää M, Latostenmaa P (2002) *Sci Total Environ* 289:97
- Casagrande L (1949) *Géotechnique* 1:159
- Casagrande L, Loughney RW (1961) *Proc 5th Int Conf Soil Mech, Paris* 2:555
- Fetzer CA (1967) *J Soil Mech Found Div* 93:85
- Bjerrum L, Moum J, Eide O (1967) *Géotechnique* 17:214
- Camberfort H, Caron C (1961) *Géotechnique* 11:203
- Glendinning S, Jones CJFP, Pugh RC (2005) *Int J Geomech* 5:138
- Esrig MI, Gemeinhardt Jr JP (1967) *J Soil Mech Found Div* 93:109
- Gray DH (1970) *Géotechnique* 20:81
- Acar YB, Gale RJ, Putnam GA, Hamed JT (1989) *2nd Int Symp Envir Geotechnology* 1:25
- Acar YB, Gale RJ, Putnam GA, Hamed JT, Wong RL (1990) *J Environ Sci Health A25*:687
- Eykholt GR (1992) PhD Dissertation. University of Texas at Austin
- Eykholt GR, Daniel DE (1994) *J Geotech Engrg* 120:797
- Acar YB, Alshawabkeh AN (1996) *J Geotech Engrg* 122:173
- Alshawabkeh AN, Acar YB (1996) *J Geotech Engrg* 122:186
- Yeung AT, Hsu C, Menon RM (1997) *J Hazard Mater* 55:221
- Musso G (2000) PhD Dissertation. Politecnico di Torino
- Alshawabkeh AN, Sheahan TC, Wu X (2004) *Mech Mater* 36:453
- Gajo A, Maines M (2007) *Géotechnique* 57:687
- Chen JL, Murdoch L (1999) *J Geotech Geoenviron Engrg* 125:1090
- Yeung AT (1994) In: Corapcioglu AY (ed) *Advances in Porous Media*, vol 2. p 309
- ASTM (2005) D 4318: Standard test methods for liquid limit, plastic limit and plasticity index of soils. ASTM Publication, Philadelphia
- ASTM (2006) D 2487: Standard practice for classification of soils for engineering purposes (Unified Soil Classification System). ASTM Publication, Philadelphia
- Jommi C, Sciotti A (2003) In: Bontempi (ed) *Proceedings of ISEC-02*, vol 3. AA Balkema Publishers, Lisse, p 2409
- Airò Farulla C, Jommi C (2005) Bilsel H, Nalbantoglu Z (eds) *Problematic Soils, Geoprob 2005*, vol 1. p 229
- Tamagnini C (1994) PhD Dissertation Università di Roma *La Sapienza*
- Comina C, Foti S, Musso G, Romero E (2008) *Geotech Test J* 31(5)
- Narasimhan B, Sri Ranjan R (2000) *J Contam Hydrol* 42:1
- Chighini S, Lancellotta R, Musso G (2002) In: Vulliet L, Laloui L, Schrefler B (eds) *Environmental geomechanics – Monte Verità 2002*, EPFL Press, Lausanne, p 329
- UNI (2004). 11140: Determination of carbon dioxide. UNI, Milano
- Albrecht BA, Benson CH (2001) *J Geotech Geoenviron Engrg* 127:67