Compressibility and residual shear strength of smectitic clays: influence of pore aqueous solutions and organic solvents

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Summary

This paper reports experimental results relative to the influence of pore fluid composition on liquid limit, compressibility and residual shear strength of three clayey soils: the Ponza bentonite, a commercial bentonite, the Bisaccia clay. Compressibility was evaluated by means of oedometer tests and the residual shear strength was determined by means of direct shear and ring shear tests. The soils were powdered and tested dry and reconstituted with distilled water, salt solutions at various concentrations and organic fluids with different dielectric constants, both lower and higher than that of water. In order to evaluate the influence of pH, some tests were carried out by using HCl solutions. The results show that the effects of so different fluids can be compared directly with reference to their static dielectric constant D. As D increases from 1 to 80, liquid limit and compression index increase and the residual shear strength decreases. The liquid limit of the materials prepared with formamide (D = 110) assumes values very close to those obtained with distilled water, whereas the compression index is slightly lower and the residual shear strength much higher than in water.

Keywords: clays, compressibility, strength, salt solutions, pH, dielectric constant

1. Introduction

The influence of pore fluid composition on clay behaviour has important implications in geotechnical engineering. As a matter of fact, clay soils, whose natural state pore fluid is generally a compound solution, may also come in contact with different aqueous solutions or with organic fluids either deliberately or accidentally. The reduction in pore water salinity may produce a decrease in strength that may affect slope stability. A specific chemical treatment can cause a lasting improvement of the mechanical properties of clays. Exposure to fresh water can cause heave of foundations on swelling clays. Exposure to concentrated leachates can produce a dramatic increase in permeability of clay liners and slurry walls.

In the scientific literature, generally, the effects of ionic aqueous solutions and organic fluids on clay behaviour are investigated separately. In particular, results for materials prepared with aqueous ion solutions are analysed with reference to ion concentration, or to pH, whereas the effects of organic solvents are analysed with reference to their dielectric constant. As far as smectitic clays are considered, it has been shown that compressibility decreases with increasing of pore aqueous solution concentration [among others: BOLT, 1956; MESRI and OLSON, 1971; BARBOUR and FREDLUND, 1989; DI MAIO, 1996a, 1998; DI MAIO et al. 2004], whereas shear strength increases [among others: KENNEY, 1967; MESRI and OLSON, 1970; DI MAIO, 1996a, 1996b, 1998; ANSON and HAWKINS, 1998]. Compressibility and rate of consolidation decrease with decreasing of dielectric constant of organic fluids, whereas permeability increases [JIMENEZ SALAS and SERRATOSA, 1953; MESRI and OLSON, 1971; SRIDHARAN and VENTAKAPPA RAO, 1973]. Shear strength of montmorillonite decreases with increasing of dielectric constant in the range 1-80 [SRIDHARAN and VENTAKAPPA RAO, 1973].

As far as kaolinite is considered, SRIDHARAN and VENTAKAPPA RAO [1973] found that, differently from montmorillonite, it may undergo consolidation as an effect of an increase in the dielectric constant D of the pore fluid. Furthermore, its compression index C_c decreases as D increases, it reaches a minimum at D=24.3, then increases until D=32 and finally remains constant [CHEN et al., 2000]. A similar dependency on D has been found also for shear strength, although the minimum was achieved for different value of D [MOORE and MITCHELL, 1974; ANANDARAJAH and ZHAO, 2000].

The available results relative to different types of pore fluid are not always comparable because of different procedures in sample preparation: from slurries, sediments from suspensions, compacted materials, and so on. The purpose of this paper is

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to compare the effects on smectitic clay behavior of water, air, salt solutions at various concentrations, acid solutions and organic solvents with different dielectric contants. The experimentation has been carried out on three powdered smectitic soils: two practically "pure" clays, the Ponza bentonite and a commercial bentonite, mostly composed of montmorillonite, and the Bisaccia clay, containing 30% montmorillonite. The influence of pore fluid composition has been evaluated on liquid limit, compression index and residual shear strength. Compression tests were carried out on materials "reconstituted" according to Burland [1990]. The shear strength was analysed at the residual value, because this is known to be a feature depending solely on the soil-fluid system, independent of the initial structure and load history of the soil. The results relative to so different fluids were analysed with reference to a single parameter, the pore fluid dielectric constant, also in the case of non-organic fluids.

2. Materials and liquid limit

The experimentation was carried out on three powdered smectitic soils: the Ponza bentonite, a commercial bentonite provided by Laviosa Chimica Mineraria S.p.A. (Livorno, Italy) and the Bisaccia clay. In the case of this latter, which is a scaly clay in nature, the complete disaggregation required powerful mechanical treatment, as suggested by Rippa and Picarelli [1977]. Particle size distribution curves, determined through combined sieve and sedimentation analyses, are reported in Figure 1. X-ray diffraction analysis showed that the two bentonites are almost pure smectites, whereas the Bisaccia clay contains 30% Ca-smectite [Di Maio et al., 2004].

According to Sridharan and Prakash [1998], an accurate evaluation of water retention properties is given by the settling limit w_{SL}, defined as the maximum water content of a soil-water suspension for which there is not a decrease in porosity caused by settling. Nevertheless, most of the available correlations with intrinsic properties of soils refer to the liquid limit. So, in order to have a first idea of the influence of pore fluid composition on the considered soils' behaviour, the liquid limit was evaluated – by means of the British fall cone test-mixing the powdered clays (oven-dried at 105°C for three day) with a number of different fluids.

In the case of salt solutions, the water content w was defined as the weight of water divided by the weight of solid (without salt). In the case of acid solutions and organic fluids, w is actually the fluid content, calculated as the weight of fluid W_f divided by the weight of solid W_s. Organic fluids with low dielectric constant tend to evaporate very rapidly at room temperature. On the contrary, organic compounds with high dielectric constant evaporate very slowly by oven drying even at 220°C. So, in the cases of cyclohexane (D=2) and formamide (D=110), W_f and W_s of each sample were measured before mixing solid and fluid. For dry materials, the void ratio e_L corresponding to 20 mm cone penetration was evaluated. In this case w_L was defined as e_L/G_S (i.e. the water content of a water saturated specimen with the same void ratio e_L as the dry specimen).

The results obtained with NaCl solutions show that w_L decreases dramatically with increasing solution molarity M (Fig. 2). The largest variations occur in the range 0-0.6 M, i.e. between rain water and sea water. So, the fluid content for which marine origin clays can become liquid *in situ* can be much lower
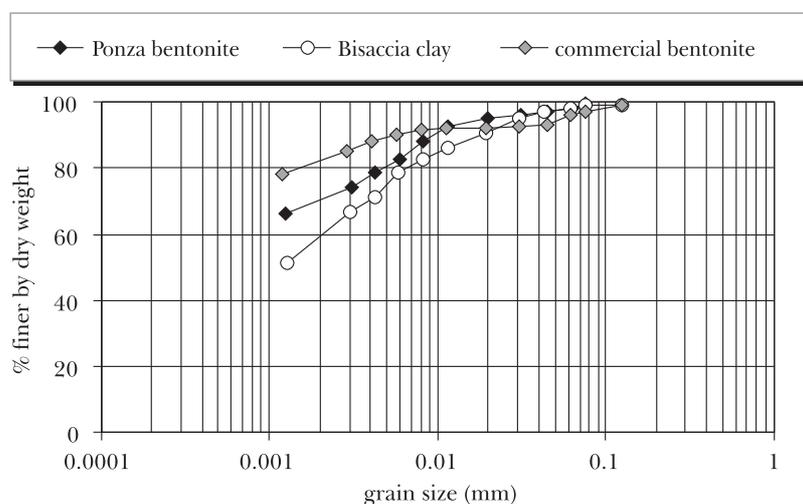

Fig. 1 – Grain size distribution curves.
Fig. 1 – Curve granulometriche.

than that determined in laboratory with distilled water. Similar effects are caused by KCl and CaCl$_2$ solutions on the Ponza bentonite [DI MAIO, 1996a]. The liquid limit of the commercial bentonite was also evaluated with other salt solutions and with HCl solutions at various pH. The results show that w_L decreases significantly with the molarity M of all considered solutions (Fig. 3). For M < 1, MgCl$_2$ solution effects seem to be stronger than those of NaCl and KCl, consistently with the cations' higher charge. HCl effects were analysed in the range of pH between 0.1 (M=0.79) and 7. Figure 3 shows that, in terms of molarity, the effects on w_L are similar to those of the salt solutions. The liquid limits were also evaluated with some organic solvents and compounds of very different dielectric constants (Fig. 4). The lowest value D=2 (at 20°C) is relative to cyclohexane, the highest, D=110, is for formamide. In order to compare the effects of these fluids to those of aqueous ionic solutions, the latter were

also analysed in terms of dielectric constant. In the case of NaCl solutions, the values of D determined experimentally [PITTS, 1995; KUSALIK and PATEY, 1988; NORTEMANN et al., 1997] were compared to those calculated through the Rayleigh model[1]. Since experimental results are very similar to the theoretical ones, the same model was used to calculate the dielectric constant of the other solutions. Table I reports the static dielectric constant of organic fluids as well as their densities. For the aqueous solutions, only the value corresponding to one concentration is specified.

Figure 4 shows that as D increases up to 70, w_L varies negligibly. In particular, it is worth noting that w_L of the Bisaccia clay reconstituted with saturated NaCl solution is very close to w_L of the material prepared with dimethylsulfoxide, an organic solvent whose dielectric constant is equal to that of the NaCl solution (D=47). For 70<D<80, w_L increases dramatically and in this range the differences
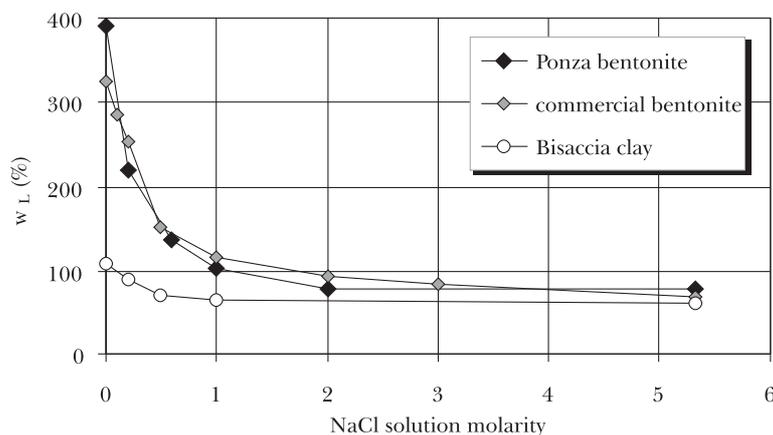
Fig. 2 – Liquid limit w_L against pore NaCl solution molarity. The limit, determined by fall cone test, is defined as the weight of water divided by the weight of solid (without salt).
Fig. 2 – Limite liquido w_L in funzione della molarità delle soluzioni di NaCl. Il limite, determinato tramite il "cono britannico", è definito come rapporto tra peso dell'acqua e peso del solido (senza sale).
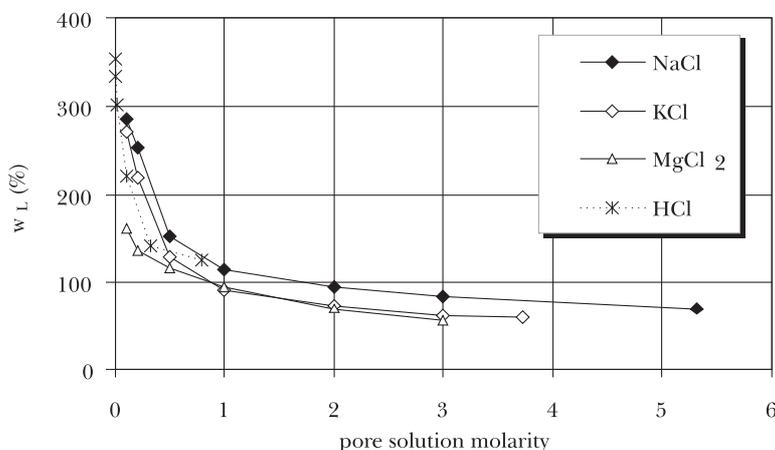
Fig. 3 – Liquid limit w_L of the commercial bentonite against pore solution molarity of various aqueous solutions.
Fig. 3 – Limite liquido w_L della bentonite commerciale in funzione della molarità delle soluzioni ioniche acquose.

Tab. I – Dielectric constant and unit weight of fluids used in the current experimentation.
Tab. I – Costante dielettrica e peso specifico dei fluidi usati in questa sperimentazione.

Fluid	Static dielectric constant (T=20°C)	Unit weight (g/cm^3)
Air	1	-
Cyclohexane	2	0.78
Ethanol	24.3	0.81
Ethylene glycol	37	1.11
Dimethyl sulfoxide	47	1.10
Distilled water	80	1.00
Formamide	110	1.13
1 M NaCl aqueous solution	68.23	1.05
1 M KCl aqueous solution	66.11	1.07
1 M MgCl$_2$ aqueous solution	68.38	1.08
HCl aqueous solution at pH=1	78.71	1.01

among different clays increase. Finally, Figure 4 shows that the values obtained with formamide, the only fluid used in this experimentation with D higher than 80, are very close to those obtained with distilled water (D=80) and do not follow the trend shown for D≤80.

3. Compressibility

Compressibility was evaluated by means of fixed-ring oedometer tests on four sets of specimens. The first set consisted of the natural soils prepared by thoroughly mixing the air-dried powders at a distilled water content higher than the liquid limit evaluated with distilled water. A clay prepared by this procedure is defined here "reconstituted", following BURLAND [1990] who considered the "reconstituted" state of structure as a reference state, and defined "intrinsic" the related properties. The second set was constituted by the air-dried powdered materials mixed with salt solutions at various concentrations. Also in this case, the initial solution content was equal or higher than the liquid limit evaluated with the same solution. For the Ponza bentonite and the Bisaccia clay reconstituted with water or with aqueous ionic solutions, the liquid limit state was found to be a reference state, even when they were prepared with concentrated salt solutions. As a matter of fact, the compression curves relative to several different initial solution contents higher than w_L were found to converge at low values of σ'_a [DI MAIO *et al.*, 2004]. Another set of tests was carried out on the materials saturated with organic fluids. In the case of cyclohexane, the reconstitution procedure was such as to account for both the tendency of the liquid to evaporate very rapidly at room temperature, and the great reduction in the paste plasticity. The powdered soils, oven-dried at 105°C for three days, were rapidly mixed with the maximum liquid content at which apparently there was no self-weight consolidation. They were placed in the oedometer cells, immersed in cyclohexane, and the cells were sealed. A preliminary experimentation showed that different reconstitution procedures, such as air-drying, oven-drying at 105°C or hydration starting from natural water content, do not cause differences in the behaviour of the water saturated specimens. So, the results of these tests can be reasonably compared to those of the first and second sets. In the case of the other organic fluids, the powders were thoroughly mixed at a fluid content equal or higher than the liquid limit evaluated with the appropriate fluid. The last set of tests was carried out on "dry" specimens. The materials,
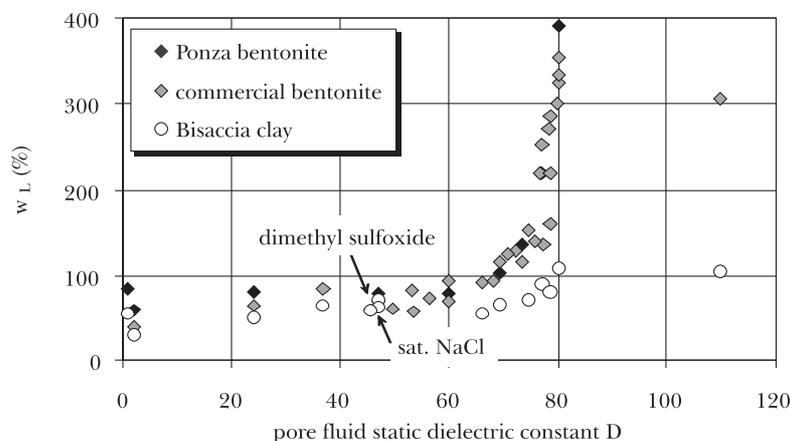

Fig. 4 – Liquid limit w_L against pore fluid static dielectric constant D.
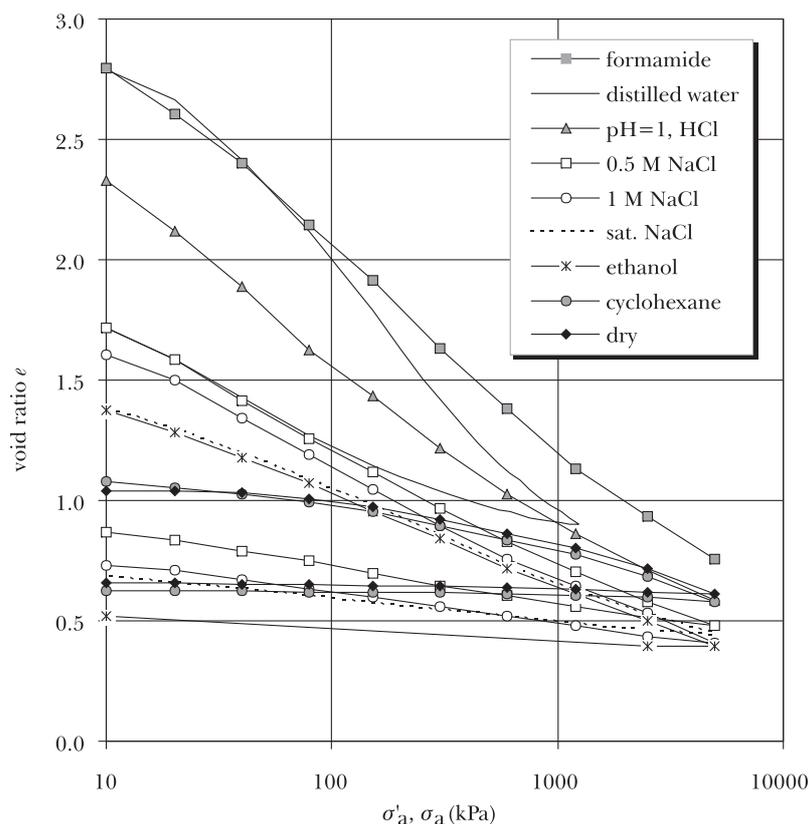*Fig. 4 – Limite liquido w_L in funzione della costante dielettrica statica D del fluido di porosità.*

Fig. 5 – Compression curves of the Bisaccia clay reconstituted with different types of pore fluids. The abscissa is σ_a for the dry specimen, σ'_a for all the other specimens.

Fig. 5 – Curve di compressione dell'argilla di Bisaccia ricostituita con vari tipi di fluido. L'ascissa è σ_a per il provino asciutto, σ'_a per tutti gli altri provini.

dried at 105°C for 3 days, were prepared in thin layers, with an initial void ratio close to that of the materials prepared with cyclohexane.

It is worth noting that cyclohexane was used because it is a non polar fluid, and so it should not give rise to repulsive forces. Furthermore, with its very low dielectric constant, it should not cause a significant variation in attractive forces with respect to air. Its role is to saturate the material and to fix the hydraulic boundary conditions. So, in theory, the only difference between the dry specimen and cyclohexane-saturated specimen should be that pore pressures of the latter are known at equilibrium.

The specimens – 2 cm thick – were loaded and subsequently unloaded by steps. Each load was sustained long enough to reach the inflection point of the curves of displacements [Di Maio and Onorati, 2000].

The comparison of the effects of different types of pore fluids reported for Bisaccia clay in terms of e–$log\sigma'_a$ (Fig. 5) shows that:

(a) the behaviour of the dry material (D=1) is very similar to that of the material reconstituted with cyclohexane (D=2) at the same initial void ratio, suggesting that the dry specimen is not significatively influenced by possible matric suction.

However, to be accurate, the compression curve of the dry material in Figure 5 refers to total axial stress;

(b) the compressibility of the material prepared with formamide is similar to that of the material prepared with distilled water for σ'_a<100 kPa; it is lower for higher stress values;

(c) the compression curves of both cyclohexane-saturated and dry materials intersect the normal compression lines of the material reconstituted with the other fluids, indicating an increase in shearing resistance at the particles' contacts.

A behaviour qualitatively similar is exhibited by the other two soils, as shown in Figure 6, which reports the compression index C_c against the static dielectric constant of the considered pore fluids. The index refers to a small increment of axial stress (from 150 kPa to 300 kPa) in order to account for the non linearity of the curves. It can be observed that as D increases up to values of about 70, C_c increases almost linearly. For 70<D<80, it increases dramatically and in this range the differences among different clays increase. The compression index of the materials prepared with the HCl solution at pH=1 is consistent with those of the other fluids. C_c of the materials prepared with formamide is
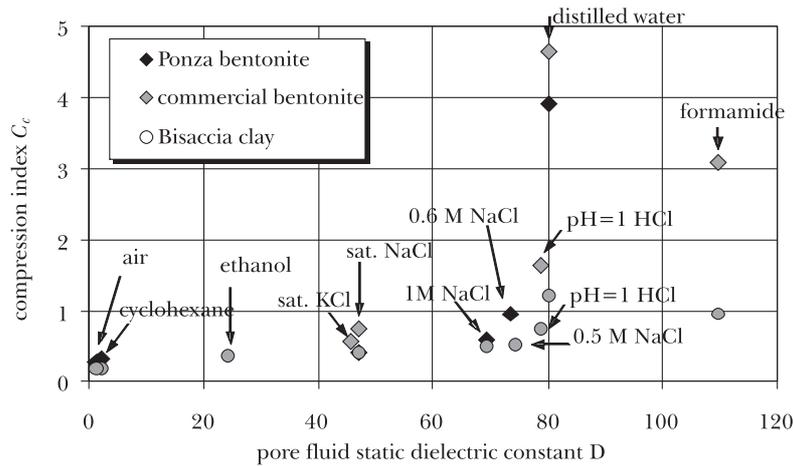
Fig. 6 – Compression index evaluated in the range 150 kPa – 300 kPa against pore fluid static dielectric constant D.
Fig. 6 – Indice di compressibilità valutato nell'intervallo 150 kPa – 300 kPa in funzione della costante dielettrica statica D del fluido di porosità.
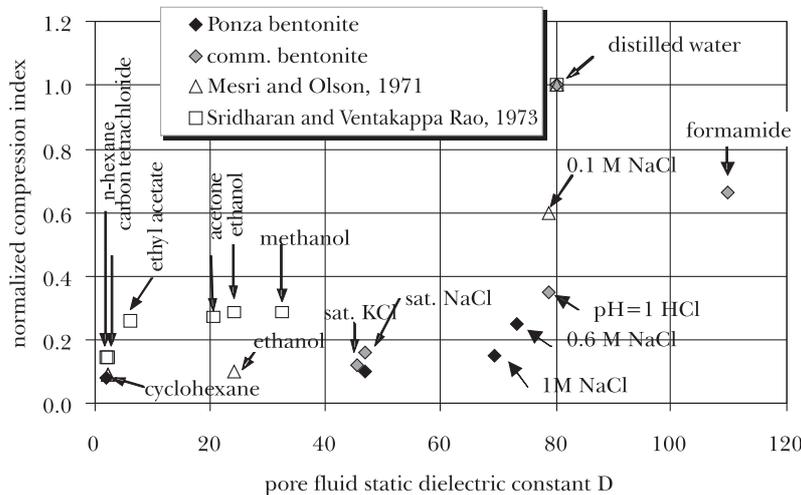

Fig. 7 – Compression index of smectitic clays, normalized with respect to C_c of materials reconstituted with distilled water, against pore fluid static dielectric constant D.
Fig. 7 – Indice di compressibilità di argille smectitiche, normalizzato rispetto a C_c dei materiali ricostituiti con acqua distillata, in funzione della costante dielettrica statica D del fluido di porosità.

lower than that obtained with distilled water. Similar trends are obtained for C_c evaluated in different stress ranges.

The results obtained for the two bentonites agree with those obtained by MESRI and OLSON [1971] on a montmorillonite reconstituted with a procedure similar to that used in this experimentation. The comparison is shown in Figure 7, which reports the compression index normalized with respect to that of the clay reconstituted with distilled water against the dielectric constant of pore fluids. As expected, the experimental data do not agree with those found by SRIDHARAN and VENTAKAPPA RAO [1973] probably because of different sample preparation, the montmorillonite used by these latter authors having been oven dried, compacted to a given density, subjected to a nominal axial pressure of about 6 kPa in a consolidation cell, subsequently

soaked by the required organic fluid and then compressed further.

It is worth noting that the trend of smectitic soils is very different from that exhibited by kaolin (Fig. 8). CHEN *et al.* [2000] carried out compression tests on kaolinite prepared with sediments from suspensions of the clay in water and in nine organic fluids. The authors showed that as the dielectric constant increases from approximately 2 in non-polar fluids to 80 in water, void ratio and compression index of the kaolinite decrease first, reaching a minimum at a dielectric constant of about 24 (ethanol), and then increase. The authors found that in the range 1<D<80 the variation is similar to that of the Hamaker constant on which the attractive van der Waals forces depend linearly. Qualitatively similar results were obtained by OLSON and MESRI [1970], as shown in the same figure. The different sample
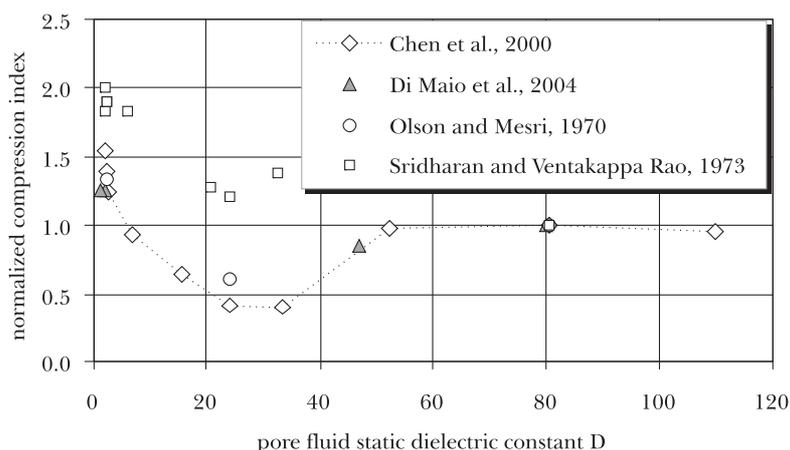
Fig. 8 – Compression index of kaolin, normalized with respect to C_c of materials reconstituted with distilled water, against pore fluid static dielectric constant D.
Fig. 8 – Indice di compressibilità del caolino, normalizzato rispetto a C_c dei materiali ricostituiti con acqua distillata, in funzione della costante dielettrica statica D del fluido di porosità.

preparation is probably the cause of the difference with data by SRIDHARAN and VENTAKAPPA RAO [1973]. For D=110, CHEN *et al.* [2000] found that the compression index was essentially the same as that at D=80, in spite of the higher Hamaker constant and then of higher attactive forces. They hypothesized that the increase in attractive forces was balanced by an increase in double layer repulsive forces,

The differences between smectite and kaolin volume change behaviour is probably due to their very different values of specific surface. Due to their large specific surfaces, volume change of smectites is primarily governed by adsorbed fluid thickness which increases dramatically in the case of water and diluted salt solutions. On the contrary, because of its low specific surface, kaolin behaviour is controlled by shearing resistance at the contact points

between particles which, in turn, depends on the balance between repulsive and attractive forces.

4. Rate of consolidation and hydraulic conductivity

The rate of consolidation is strongly influenced by pore fluid composition, as shown in Figure 9, which reports the oedometric consolidation curves relative to an axial stress increment from 40 kPa to 80 kPa, obtained for the Bisaccia clay reconstituted with various fluids. The coefficient of consolidation c_v – determined from the experimental curves of displacement by the log-time Casagrande method (based on the Terzaghi model) – decreases as the dielectric constant increases up to 80 (Fig. 10). The coefficient of consolidation of the material prepared
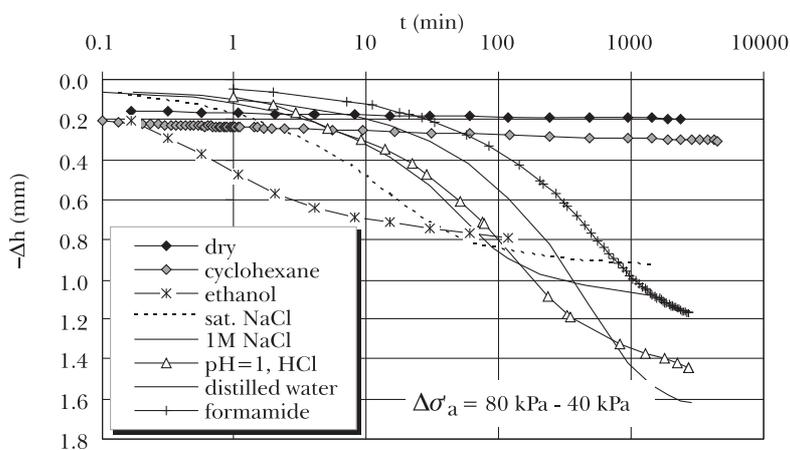

Fig. 9 – Consolidation curves of the Bisaccia clay reconstituted with different fluids for an increment of axial stress from 40 kPa to 80 kPa.
Fig. 9 – Curve di consolidazione dell'argilla di Bisaccia ricostituita con vari fluidi per un incremento di tensione assiale da 40 kPa a 80 kPa.
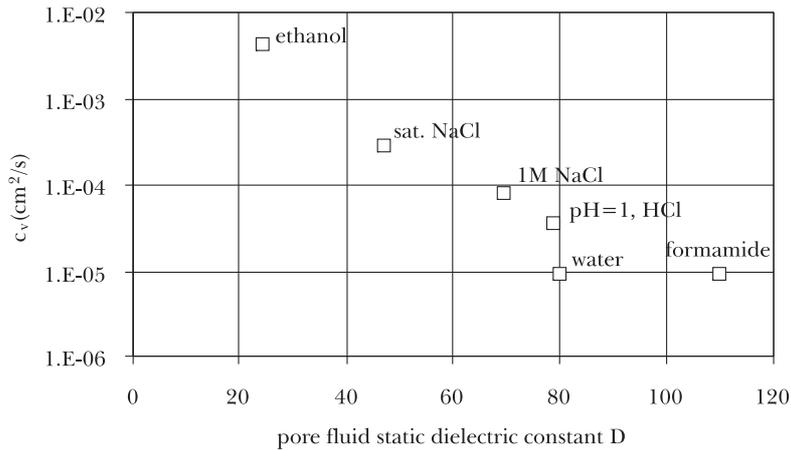
Fig. 10 – Coefficients of consolidation of the Bisaccia clay reconstituted with different fluids relative to an increment of axial stress from 40 kPa to 80 kPa.
Fig. 10 – Coefficienti di consolidazione dell'argilla di Bisaccia ricostituita con vari fluidi, per un incremento di tensione assiale da 40 kPa a 80 kPa.
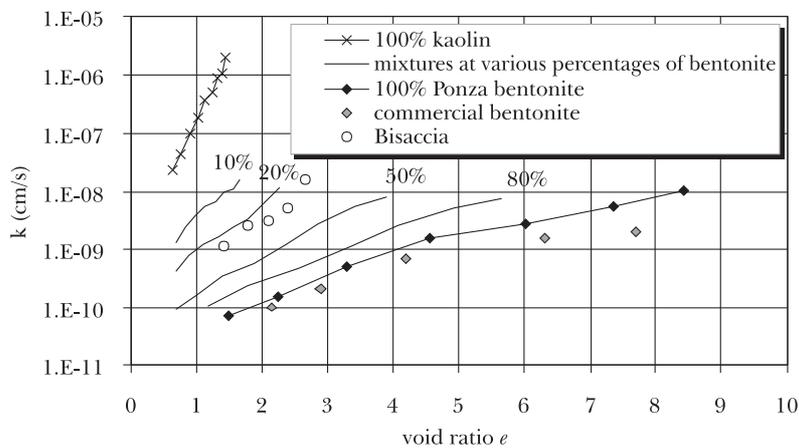

Fig. 11 – Hydraulic conductivity k against void ratio *e* of Ponza bentonite-kaolin mixtures, commercial bentonite and Bisaccia clay reconstituted with distilled water.
Fig. 11 – Conducibiltà idraulica k in funzione dell'indice di porosità e *per miscele di bentonite di Ponza e caolino, bentonite commerciale e argilla di Bisaccia ricostituite con acqua distillata.*

with formamide is close to that obtained with water. Consolidation of the material prepared with cyclohexane was extremely rapid and it was not possible to evaluate c_v. Only under the increment of axial stress from 2500 kPa to 5000 kPa it was possible to compute a value of 0.016 cm²/s.

Under the hypothesis of the Terzaghi model of one-dimensional consolidation, approximate values of the hydraulic conductivity k in the axial direction were obtained from the relation $c_v = k/(m_v \gamma_{fl})$, where m_v is the compressibility coefficient and γ_{fl} the pore fluid unit weight (Tab. I). Figure 11 reports k against void ratio for the three materials and, for comparison, for mixtures bentonite-kaolin with a given percentage of Ponza bentonite dry weight. All the materials were reconstituted with distilled water at their liquid limit. As expected, differences up to four degrees of magnitude are found between kao-

lin and bentonite; 10% bentonite is sufficient to cause large decrease in hydraulic conductivity with respect to kaolin. The values obtained for the Bisaccia clay are very close to those obtained for the artificial mixtures with a similar percentage of montmorillonite. Figure 12 reports the results relative to Bisaccia clay reconstituted with different fluids. It can be observed that variations due to pore fluid can be of three orders of magnitude.

The strong variability in k cannot be explained by free fluid viscosity, since this latter varies less than 20% for the used fluids. MESRI and OLSON [1971] explained the strong influence of pore organic fluids on hydraulic conductivity of the Wyoming bentonite prepared with carbon tetrachloride and benzene in terms of changes in fabric and formation of particle aggregates. Besides possible structural effects, which were not investigated in this
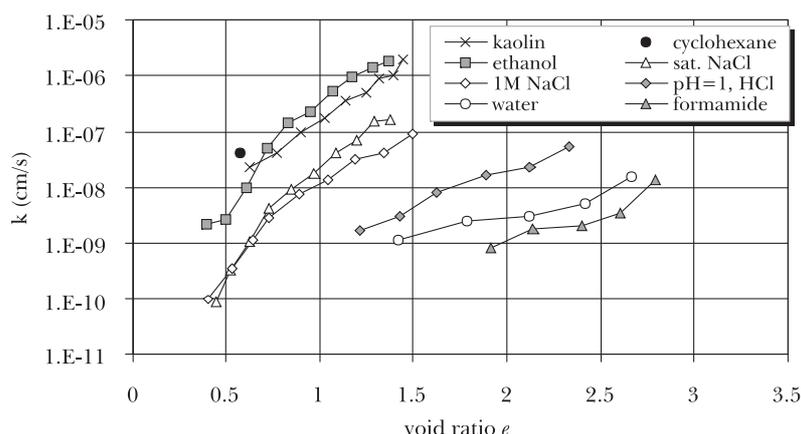
Fig. 12 – Hydraulic conductivity k of the Bisaccia clay reconstituted with different pore fluids.
Fig. 12 – Conducibiltà idraulica k dell'argilla di Bisaccia ricostituita con vari fluidi.

study, the decrease of the thickness of the fluid strongly attracted by the clay particles probably affects the hydraulic conductivity.

5. Residual shear strength

Experimental results reported in the scientific literature show that the residual shear strength is a characteristic of the system solid-pore fluid, independent of initial fabric and load history. Furthermore, the analysis of the behaviour of different soils shows that for c.f. <20%–25%, the residual friction angle φ'_r is close to the critical state friction angle [SKEMPTON, 1985]. For 25%<c.f.<50%, results are extremely scattered. For c.f. > 50% the residual friction angle of a soil is equal to that of its clay component and its value may vary greatly with the type of clay. [LUPINI *at al.*, 1981]. When the clay fraction contains montmorillonite, this component becomes the most influential: 20%–25% dry weight is sufficient to reduce the residual shear strength of the mixture to that of the clay itself [KENNEY, 1967; DI MAIO and FENELLI, 1994; DI MAIO, 1996b]. So, the three soils used in this experimentation are expected to exhibit the same residual strength.

Kenney was one of the first who analysed the influence of pore solution composition on residual shear strength. His results relative to artificial mixtures show that in the case of the mixture quartz-Na-montmorillonite, the influence of pore fluid composition is noticeable even for clay content as low as 20% dry weight. Similar results were found also for bentonite-kaolin mixtures [DI MAIO and FENELLI, 1994].

Most of published results refer to materials prepared with aqueous solutions. This study was performed in order to compare the effects of the latter with those of other types of fluids. Residual shear strength was determined by using the conventional Casagrande box and the Bishop ring shear appara-

tus. In the first case, for each value of axial stress, the specimens were sheared back and forth until the minimum strength was obtained. Rates of displacement in the range 0.001-0.005 mm/min were adopted. Various pore fluids were used: water, salt solutions at various concentrations and organic solvents and compounds with different dielectric constants, both lower and higher than that of distilled water. Dry materials were also sheared. In the case of low dielectric constant fluids, the shear surface was often very irregular. So, frequently, during the tests the specimens were cut manually in order to ensure the flatness of the shear surface. Moreover, at the end of the test, the shear surface was carefully observed and only the results relative to specimens with a planar surface were considered. In some cases, when the residual shear strength for a given solid-pore fluid system had been attained, the specimens were exposed to a different fluid, as shown in Figure 13, that refers to a dry specimen of Bisaccia clay that was exposed to ethanol during a ring shear test. In this case, exposure caused a noticeable decrease in strength. On the contrary, exposure to cyclohexane did not cause but a small decrease in strength.

Figure 14 reports some results of shear tests relative to Bisaccia clay in terms of τ_r-σ'_n. The results obtained by using the ring shear are clearly indicated in the figure. All the other results refer to Casagrande direct shear box. The cohesion intercept being null, it is possible to interpret the results in terms of residual friction angle φ_r. The latter parameter is 29° for the Bisaccia clay prepared with cyclohexane or dry, 19° for the material prepared with ethanol and ethylene glycol, 14° for the material reconstituted with a saturated NaCl solution, 5.5° in HCl solution at pH=1 and 4.5° in water. The material reconstituted with formamide exhibits a value of φ_r very close to that of the material reconstituted with the concentrated salt solutions. Simi-
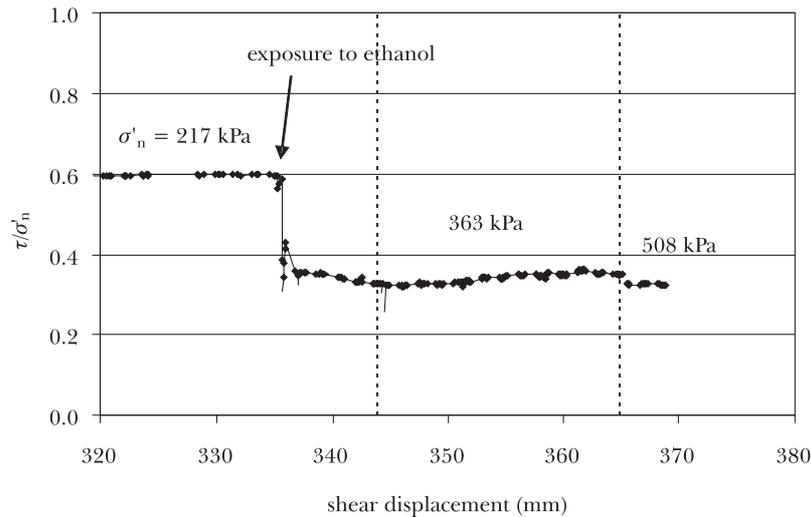
Fig. 13 – Shear strength against shear displacement for a dry specimen of the Bisaccia clay which was exposed to ethanol at about 335 mm displacement.
Fig. 13 – Resistenza a taglio in funzione dello scorrimento per un provino asciutto di argilla di Bisaccia che è stato esposto a etanolo dopo circa 335 mm di scorrimento.
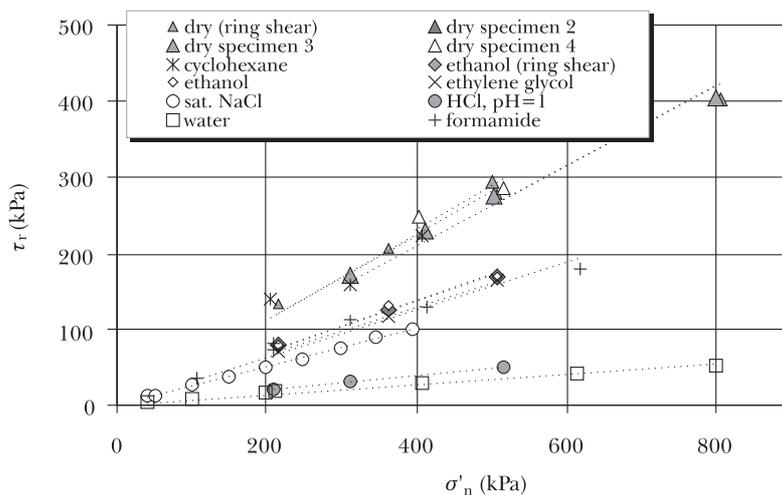

Fig. 14 – Residual shear strength against normal stress for the Bisaccia clay prepared with different pore fluids.
Fig. 14 – Resistenza residua in funzione della tensione normale per l'argilla di Bisaccia preparata con vari fluidi.

lar results were obtained for the two bentonites (Fig. 15). Other results obtained on Bisaccia clay and Ponza bentonite reconstituted with salt solutions at various concentrations are reported by DI MAIO [1996a, 1996b]. Figure 16 reports all the available ratios τ_r/σ'_n of the considered materials against the pore fluid dielectric constant. As D increases from 1 to 47, for the used materials and fluids, the residual shear strength decreases. D=47 refers to both saturated NaCl solution and dymethylsulfoxide. The Ponza bentonite exhibited practically the same value of residual shear strength when reconstituted with these fluids so different. The repulsive barrier of the system clay-dimethyl sulfoxide is known to be very low. The experimental results suggest that also the repulsive barrier with the saturated solution is negligible. As the solution molarity decreases from saturation to 1 M, corresponding to D=69.5, the resultant of the attractive and repulsive forces probably remains constant, considered that the material exhibits almost the same value of strength as for saturated solution and dymethyl sulfoxide. For D higher then 69.5 and lower than 80, the ratio τ_r/σ'_n decreases dramatically. This is the range of aqueous ion solution whose concentration decreases from 1 M to negligible values (distilled water). In this range, double layer repulsive forces increase, reaching the maximum with distilled water. For D =110, due to the low solubility of salts in formamide, the repulsive forces decrease and τ_r/σ'_n increases again.
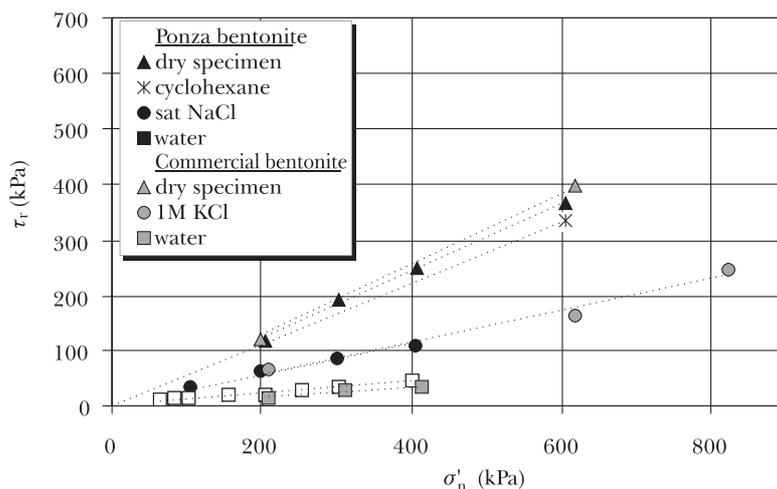
Fig. 15 – Residual shear strength against normal stress for the Ponza and commercial bentonites prepared with different pore fluids.
Fig. 15 – Resistenza residua in funzione della tensione normale per le bentoniti di Ponza e commerciale preparate con vari fluidi.
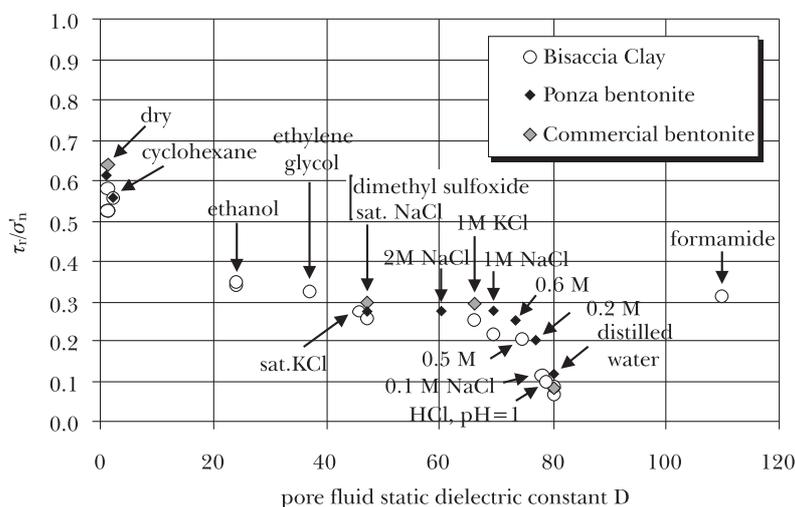

Fig. 16 – Ratio τ_r/σ'_n against pore fluid static dielectric constant D for the tested soils prepared with different fluids.
Fig. 16 – Rapporto τ_r/σ'_n in funzione della costante dielettrica statica D del fluido di porosità per i terreni studiati, preparati con vari fluidi.

So, the minimum of strength is obtained when the pore fluid is distilled water, at least for the systems clay-pore fluid analysed here. Natural state pore liquid is often a composite solution, hence the use of distilled water for laboratory tests would not be appropriate. ANSON and HAWKINS [1998] briefly discussed the implication for slope stability analysis of using deionized water in laboratory tests, suggesting that the difference between results calculated by back analysis and those obtained in laboratory could be due, at least in part, to the use of deionized water.

6. Conclusions

Results of oedometric compression tests and shear tests are presented for three smectitic soils re-

constituted with different pore fluids, saline solutions, acid solutions, organic solvents and compounds, water and air. The influence on liquid limit, compression index and residual shear strength is investigated. Some results relative to hydraulic conductivity deduced from consolidation curves are also reported. The results have been analysed with reference to the static dielectric constant of the pore fluid, even in the case of aqueous ion solutions.

Differently from kaolin, the minimum of strength and hydraulic conductivity, and the maximum of liquid limit and compressibility are obtained for the materials prepared with distilled water. The behaviour of smectitc clays reconstituted with distilled water is thus an "extreme behaviour", which could be very different from the behaviour *in situ*. So, the evaluation of the behaviour of a given

clay-pore fluid system by laboratory testing would require the use of the appropriate fluid.

Acknowledgements

Notes

* The Rayleigh model is given by:

$$\frac{\varepsilon_m - 1}{\varepsilon_m + 2} = f_1 \frac{\varepsilon_1 - 1}{\varepsilon_1 + 2} + f_2 \frac{\varepsilon_2 - 1}{\varepsilon_2 + 2}$$

Where ε_m is the dielectric constant of the mixture; ε_1, ε_2, f_1 and f_2 are respectively the dielectric constants and volume fractions of its component (1) and (2).

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Compressibilità e resistenza residua di argille smectitiche: influenza della composizione del fluido interstiziale (soluzioni acquose e solventi organici)

Sommario

Questo articolo riporta una serie di risultati sperimentali riguardanti gli effetti della composizione del fluido di porosità su limite liquido, compressibilità e resistenza residua a taglio di tre terreni argillosi: la bentonite di Ponza, una bentonite commerciale e l'argilla di Bisaccia. La compressibilità è stata valutata attraverso prove edometriche, mentre la resistenza residua è stata ottenuta tramite prove di taglio diretto e anulare. I terreni sono stati ricostituiti con acqua distillata, soluzioni saline a varie concentrazioni e fluidi organici con diverse costanti dielettriche, sia minori che maggiori di quella dell'acqua. Alcuni provini sono stati sottoposti a prova dopo disidratazione a 105°C. Allo scopo di valutare l'effetto del pH, alcune prove sono state eseguite utilizzando soluzioni di HCl. I risultati mostrano che gli effetti di fluidi così diversi possono essere confrontati facendo riferimento alla loro costante dielettrica statica D. Al crescere di D da 1 a 80, il limite liquido e l'indice di compressibilità aumentano, mentre la resistenza residua diminuisce. Il limite liquido dei materiali preparati con formammide (D = 110) assume valori molto prossimi a quelli ottenuti con acqua distillata, mentre l'indice di compressibilità è leggermente inferiore e la resistenza residua molto più elevata.

Parole chiave: *argille, compressibilità, resistenza, soluzioni saline, pH, costante dielettrica*