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POROUS MEDIA GEOMECHANICS AND
BIOMECHANICS

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CONTENTS

Influence of pore fluid composition on volume change. Behaviour of clays exposed to the same fluid as the pore fluid <i>by C. Di Maio</i>	1
Consolidation, swelling and swelling pressure induced by exposure of clays soils to fluids different from the pore fluid <i>by C. Di Maio</i>	19
Shear strength of clays and clayey soils: the influence of pore fluid composition <i>by C. Di Maio</i>	45
Swelling media: concepts and applications <i>by J.M. Huyghe and P.H.M. Bovendeerd</i>	57
Chemo-mechanical interactions in geological and biological materials: examples <i>by B. Loret, A. Gajo and F.M. Simões</i>	125
Multi-phase multi-species mixtures <i>by B. Loret and A. Gajo</i>	149
Constitutive equations for homoionic clays <i>by B. Loret and A. Gajo</i>	165
Constitutive equations for heteroionic clays <i>by A. Gajo and B. Loret</i>	185
Mass transfer through membranes and generalized diffusion <i>by A. Gajo and B. Loret</i>	205
Finite element formulation, and simulations of laboratory tests <i>by A. Gajo and B. Loret</i>	219
Swelling shales and compacting cakes <i>by J.D. Sherwood</i>	239
Molecular modelling of pore fluids in clays <i>by N. Skipper</i>	301
Polyelectrolyte gels: basics, modelling and simulation <i>by Th. Wallmersperger, B. Kröplin and R.W. Gülch</i>	333

Consolidation, Swelling and Swelling Pressure Induced by Exposure of Clay Soils to Fluids Different from the Pore Fluid

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Abstract. This paper reports experimental results relative to volume changes caused by exposure of clay soils to fluids different from the pore fluid. Furthermore it reports some results relative to the influence of pore fluid composition on the swelling pressure of an active smectitic clay. The experimentation on volume change behaviour was carried out on several clay soils with different grain size distribution and mineral composition. The results show that exposure of water saturated Ponza bentonite to NaCl, KCl and CaCl₂ solutions causes consolidation. At high void ratio, pores and fissures form. On re-exposure to water, Na⁺ effects are reversible and the material swells noticeably. On the contrary, Ca²⁺ and K⁺ make swelling potential decrease greatly because they substitute Na⁺ as counterions. Under low values of axial stress and high void ratio, potassium and calcium effects can be reverted by exposing the material to concentrated NaCl solutions. The effects of exposure to electrolytes of soils with a smectite content between 10 % and 30 % - such as Bisaccia, Gela and Marino clays - are lower than those on the Ponza bentonite, however they are noticeable. Furthermore, depending on axial stresses, type of solution and on types of exchangeable cations, swelling caused by subsequent exposure to distilled water can be lower or higher than previous consolidation. The commercial kaolin, the Potenza and the Villa d'Agri clays undergo small consolidation as an effect of exposure to the salt solution and further large consolidation because of subsequent exposure to water. The Milazzo clay undergoes swelling because of exposure to NaCl solution. The results relative to volume change can be interpreted qualitatively in terms of double layer processes, ion exchange and initial fabric. Results relative to swelling pressure show that Bolt's model interprets satisfactorily the behaviour of the Bisaccia clay reconstituted with a concentrated salt solution and exposed to distilled water. As expected, the model interprets only qualitatively the behaviour of the material exposed to concentrated salt solutions.

1 Introduction

Exposure of active clays such as smectites to fluids with ion concentration higher or – in the case of organic fluids – dielectric constant lower than that of the pore fluid, can cause volume decrease (Mitchell et al., 1973; Barbour and Fredlund 1989; Sridharan, 1991; Di Maio, 1996a; 1996b). During the chemically induced volume change, fissures and cracks can open and permeability can increase greatly, notwithstanding the overall volume decrease (Barbour, 1987). This process can occur in clay barriers of waste disposal systems as an effect of the

interaction with leachates. It often occurs in bentonite layers used as “impermeable” protection to retaining walls, probably as an effect of chemical interaction with concrete calcium ions.

On exposure to water, active clays exhibit tendency to swell. Chemically induced swelling depends on the composition of the clay, on the composition of the pore fluid, on void ratio and stress level. At low stress level, swelling caused by exposure to water of clays reconstituted with a concentrated salt solution can be extraordinarily high. Some experimental results relative to marine origin clay shales show that interaction with rain water is the most probable cause of the large difference in water content and shear strength between the upper layer, which is often a few meters thick, and the underlying material (Di Maio and Onorati, 2000a; 2000b).

Swelling pressure can be defined as the pressure required to keep a soil element at constant volume, when hydraulic or chemical conditions are such as to induce a tendency to volume increase. In actual applications, swelling pressure is a very important parameter for the design of structures interacting with swelling soils and rocks. It must be evaluated in order to prevent damage to tunnels and to any stiff support of excavation surfaces, as well as in order to design safe shallow foundations, both in the case they are designed to resist differential movements and in the case they are designed to adjust to them by means of flexible construction (Abduljauwad et al., 1998). Furthermore, in order to prevent opening of cracks and fissures, high swelling pressure must be a property of materials constituting impermeable barriers. Exposure to a fluid whose ionic force is lower or whose dielectric constant is higher than that of the pore fluid is among the possible causes of high swelling pressure.

This paper reports experimental results relative to volume changes caused by exposure of clay soils of different composition to fluids different from the pore fluid. Some results relative to the influence of pore fluid composition on swelling pressure are also reported.

2 Materials and Methods

The experimentation was carried out on several different soils. The Ponza bentonite, Bisaccia and Marino clays, and the commercial kaolin are described in the companion paper on the influence of pore fluid composition on volume change behaviour of clays exposed to the same fluid as the pore fluid. Besides these soils, a very active commercial bentonite was also tested, with a clay fraction higher than that of the Ponza bentonite (Figure 1). Some tests were carried out on the Gela, Villa D’Agri, Milazzo and Potenza soils. The liquid limits of the four latter soils are: 149 %, 53 %, 58 % and 30 % respectively; their clay fractions: 73 %, 38 %, 45 %, 25 %. The liquid limit of the commercial bentonite was evaluated by mixing the air-dried powder with different salt solutions at various concentrations and with HCl solutions at various pH. The results show that w_L decreases dramatically with the molarity of all the considered solutions (Figure 2). $MgCl_2$ and $CaCl_2$ solutions effects seem to be higher than those of NaCl and KCl solutions. It is interesting to observe that HCl effects are similar to those of the first two solutions up to 0.32 M which corresponds to $pH = 0.5$.

Reconstituted materials were prepared by mixing the powdered soils with a given fluid to a slurry at about the liquid limit. Volume change response of exposure to fluids different from the pore fluid was evaluated in the course of fixed-ring oedometer tests. The specimens (2 cm thick) were first consolidated to fixed axial stress, doubling the pressure for successive loads. Subsequently they were exposed to a given fluid by replacing the cell fluid. Swelling pressure was evaluated by using Geonor continuous oedometer swelling equipment in a strained controlled manner, and by means of conventional oedometers with controlled axial load.

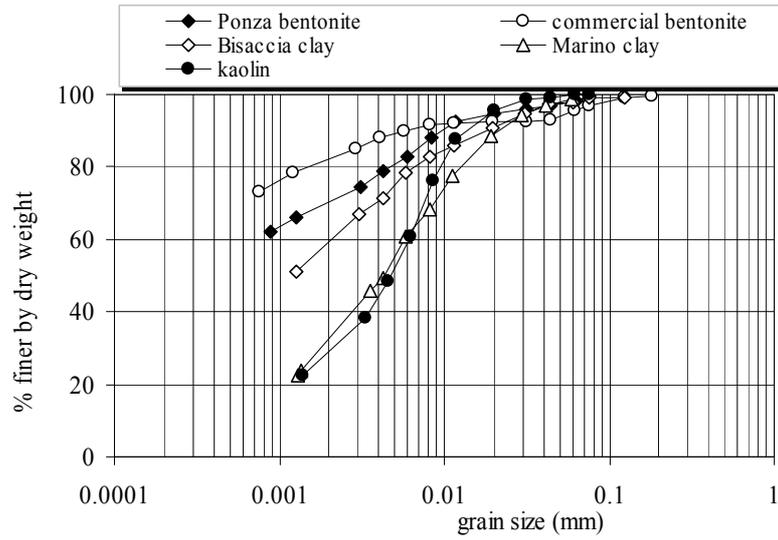


Figure 1. Grain size distribution curves of the commercial bentonite and of the other materials.

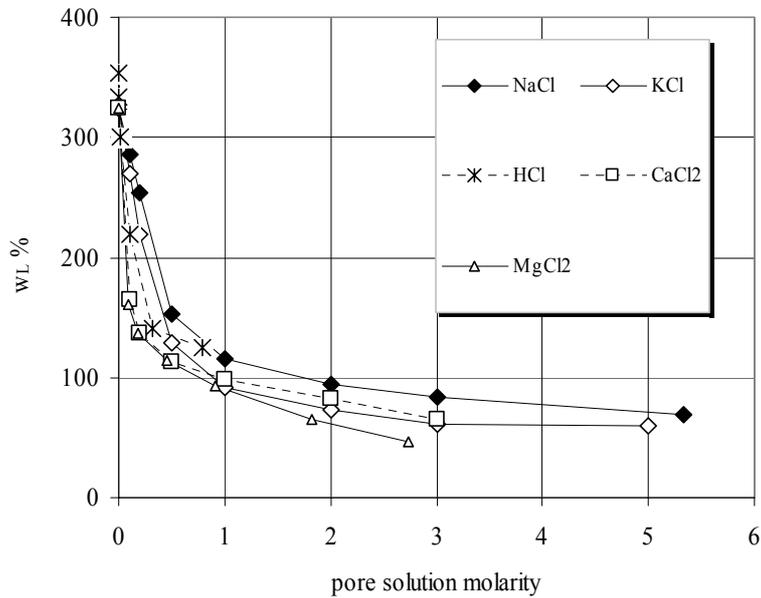


Figure 2. Liquid limit w_L of the commercial bentonite against molarity of pore solutions.

3 Chemically induced volume changes

The results relative to the Ponza bentonite are easier to interpret than those relative to the other considered soils. In fact, since it is a practically pure Na-montmorillonite, exposure to NaCl solutions doesn't cause that negligible ion exchange and thus it is possible to analyse separately the influence of pore solution concentration. The behaviour of the other natural soils is more complex because their clay minerals are heteroionic and exposure to a salt solution generally causes also ion exchange.

So, the results relative to the Ponza bentonite and some results relative to the commercial bentonite will be analysed first, and then those relative to the other soils.

3.1 Bentonite

3.1.1 Exposure to salt solutions. The technical literature reports several experimental results relative to the effects of such exposure (among others: Barbour and Fredlund, 1989; Di Maio, 1996a; 1996b; 1998). As an example, Figure 3 reports compressive volumetric strains against time for a specimen of the Ponza bentonite prepared with water at the liquid limit. The curve on the left represents consolidation for an increment of axial stress from 20 kPa to 40 kPa. Once the equilibrium had been reached, the cell water was substituted by a saturated NaCl solution. This substitution produced further consolidation, represented by the curve on the right of the arrow. Pore pressure measurements showed that this compression occurred under constant Terzaghi's effective stresses; so, in terms of void ratio e against $\log \sigma'_a$, it is a straight line normal to the abscissa. As axial stress increases and initial void ratio decreases, consolidation caused by exposure to the salt solution decreases (Figure 4).

Effects analogous to those caused by NaCl solution are caused also by other salt solutions (Figure 5) or by other fluids with more complex composition (Figure 6). In order to observe directly the process occurring during chemically induced consolidation, a specimen was mounted in a transparent oedometer and observed during exposure to a 1 M CuSO₄ solution. During the chemical consolidation, the specimen shrank and large pores and fissures were observed to form (Figure 7). This process was observed in laboratory under values of axial stress lower than 80 kPa on normally consolidated Ponza bentonite. Obviously, such an effect makes permeability increase greatly. For higher stresses, the phenomenon does not occur, at least at a macroscopic level, and at least in times of laboratory tests.

3.1.2 Re-exposure to distilled water. In order to test the reversibility of salt effects, when equilibrium was reached under the new conditions imposed by the electrolytes, the specimens which had been previously exposed to salt solutions, were re-exposed to distilled water. Such exposure caused noticeable swelling of the material which had been previously exposed to NaCl solution. On the contrary, it caused much lower effects on the materials which had been exposed to KCl and CaCl₂ solutions.

Figure 8 refers to a water saturated specimen of the Ponza bentonite that had been previously consolidated in oedometer at 40 kPa, and then exposed alternately to salt solutions and to water. After seven cycles of exposure to a saturated NaCl solution and to water, the specimen was exposed to a saturated KCl solution. Under these new conditions, exposure to water, which followed the chemical consolidation, caused a much lower swelling than during the previous

cycles. Analogous swelling behaviour was exhibited in the second cycle of exposure to KCl solution and then to water. Afterwards, the specimen was exposed to a saturated NaCl solution

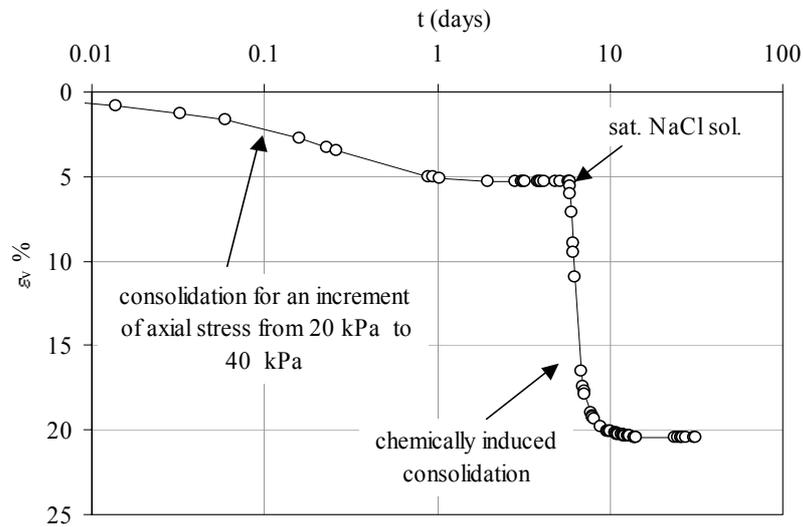


Figure 3. Mechanical consolidation and consolidation caused by exposure of the Ponza bentonite to a saturated NaCl solution.

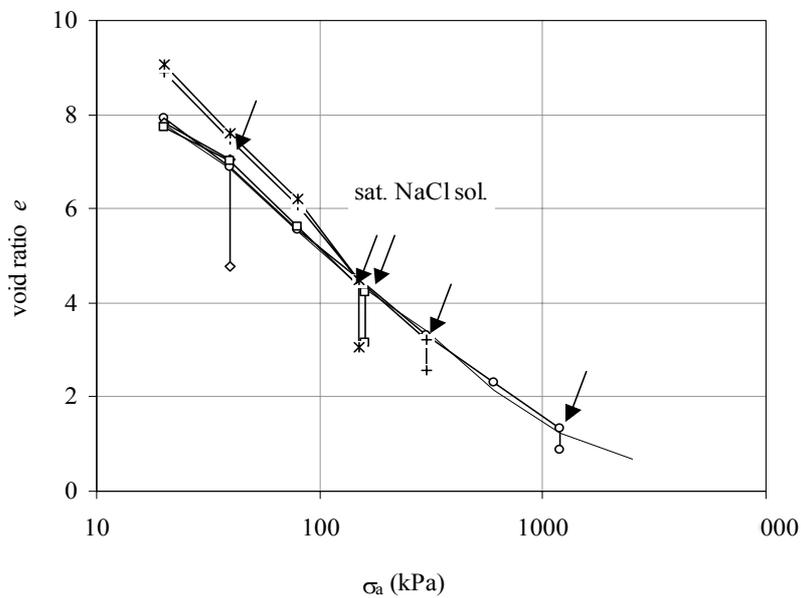


Figure 4. One-dimensional compression curves of the Ponza bentonite reconstituted with distilled water, initially compressed while submerged in water, and subsequently exposed to a saturated NaCl solution.

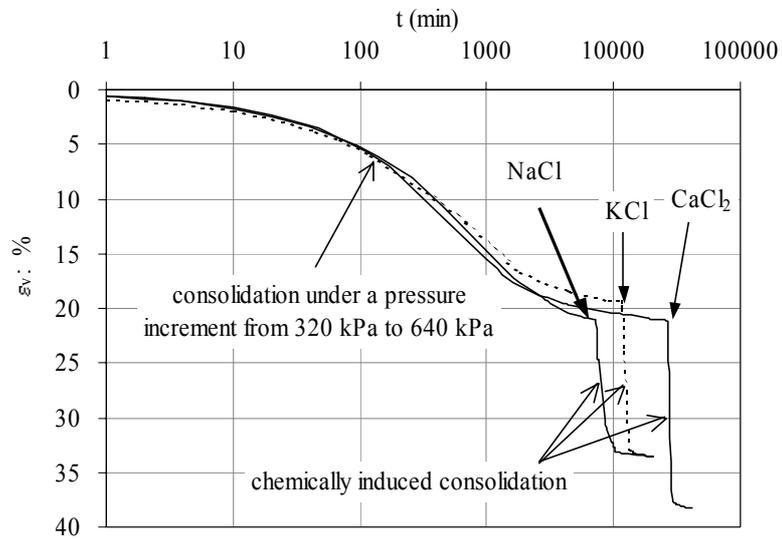


Figure 5. Consolidation of the Ponza bentonite caused by exposure to saturated NaCl, KCl and CaCl₂ solutions.

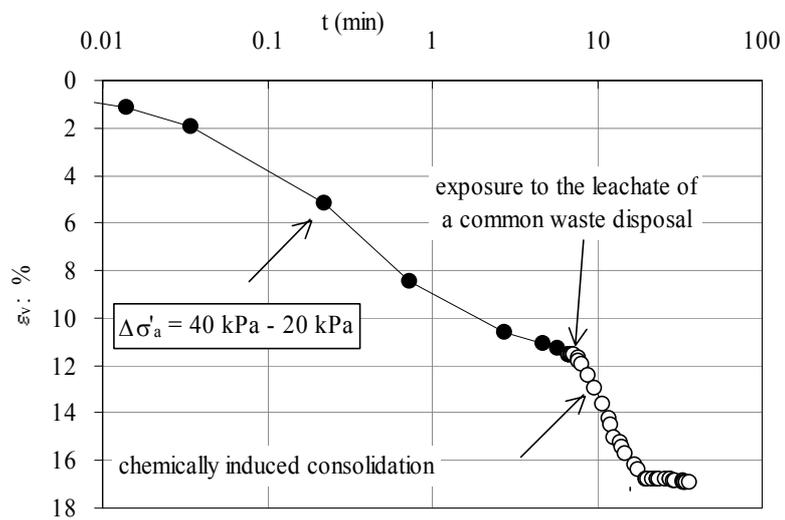


Figure 6. Consolidation of the Ponza bentonite caused by exposure to a common waste disposal leachate.

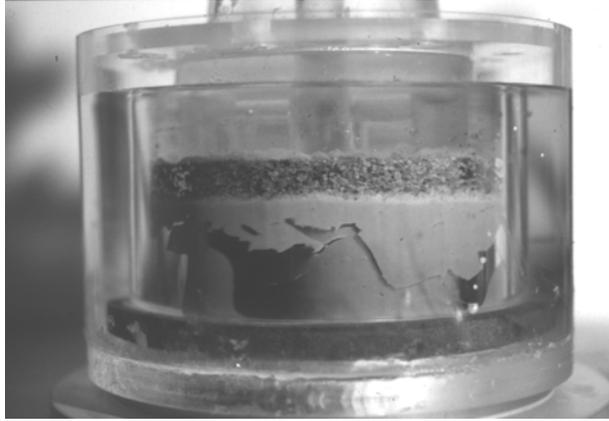


Figure 7. Ponza bentonite after exposure to a 1 M CuSO_4 solution.

and then to water. The latter exposure caused a very large osmotic swelling, close to that obtained before using KCl, thus showing that K^+ effects can be reverted by imposing appropriate conditions. Analogous behaviour was manifested by the material after exposure to CaCl_2 . Exposure to water after the osmotic consolidation did not cause any volume increase. Subsequent exposure to a saturated NaCl solution caused a further small consolidation, and the following exposure to water caused large swelling. This behaviour, which can be reasonably considered as an indirect evidence of the occurrence of ion exchange, has been observed also on other smectitic soils.

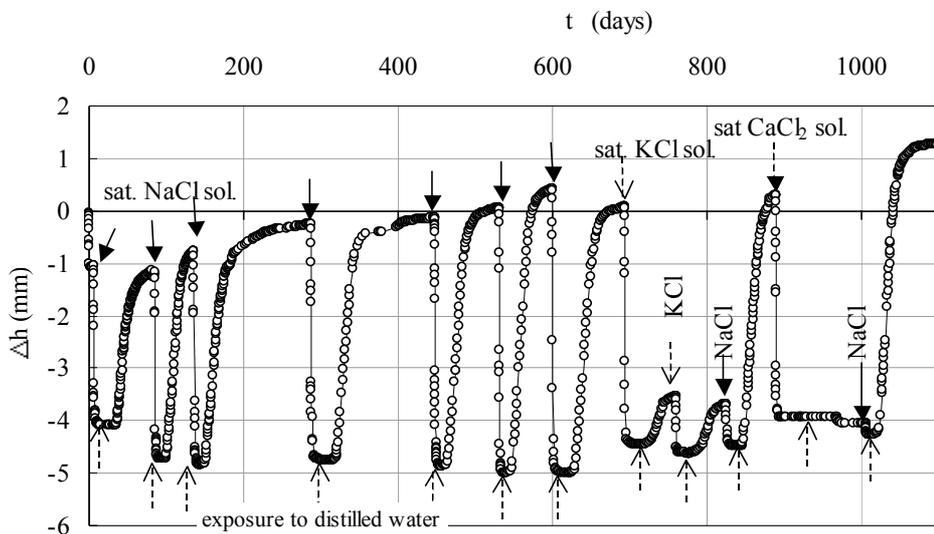


Figure 8. Consolidation caused by exposure to salt solutions and swelling caused by exposure to distilled water of a specimen of Ponza bentonite reconstituted with distilled water (Di Maio, 1998).

3.1.3 Influence of stress level and stress history. Figure 9 refers to two specimens of the Ponza bentonite reconstituted with distilled water. The specimens were one-dimensionally consolidated under axial stresses equal to 40 kPa and 960 kPa respectively. At equilibrium, they were exposed to a concentrated NaCl solution. Such exposure caused volume decrease. At equilibrium, the specimens were exposed to distilled water: this caused swelling. The figure shows that osmotic consolidation decreases with axial stress increasing (i.e. with void ratio decreasing). Furthermore, swelling is practically equal to the previous chemically induced consolidation at low axial stress, it is lower under higher values of axial stress.

However, if the material that undergoes osmotic consolidation at the higher external axial stresses is unloaded and then re-exposed to distilled water, swelling becomes such as to reach the swelling curve of the water-saturated material. This is shown by Figure 10 which reports the results of oedometer tests on four specimens of the Ponza bentonite. Specimen *a* was reconstituted with distilled water at about the liquid limit and immersed in distilled water. Specimen *b* was reconstituted with a saturated NaCl solution at the liquid limit evaluated with the same solution and immersed in it. Specimens *c* and *d* were prepared as specimen *a* and, after consolidation at 1500 kPa and 40 kPa respectively, they were exposed to a saturated NaCl solution, by simply replacing the cell fluid. Such exposure caused consolidation represented by straight lines normal to the abscissa. At equilibrium the specimens were loaded and then unloaded. After swelling at 40 kPa and at 20 kPa respectively, specimens *c* and *d* were exposed to distilled water again. This produced an increase in void ratio which made the specimens reach the swelling curve of specimen *a*. It is interesting to observe the behaviour of specimens with different load history. Figure 11 reports the results relative to a specimen of the Ponza bentonite which was exposed to the saturated NaCl solution under low void ratio, while on a re-compression curve. It was loaded up to 1200 kPa, unloaded until 10 kPa and then re-loaded. At 300 kPa the specimen was exposed to a saturated NaCl solution and this caused consolidation. At the end of consolidation, the specimen was exposed to distilled water and water was continuously renewed in order to remove ions which could have diffused from the pore solution. In this case, swelling was practically equal to previous consolidation.

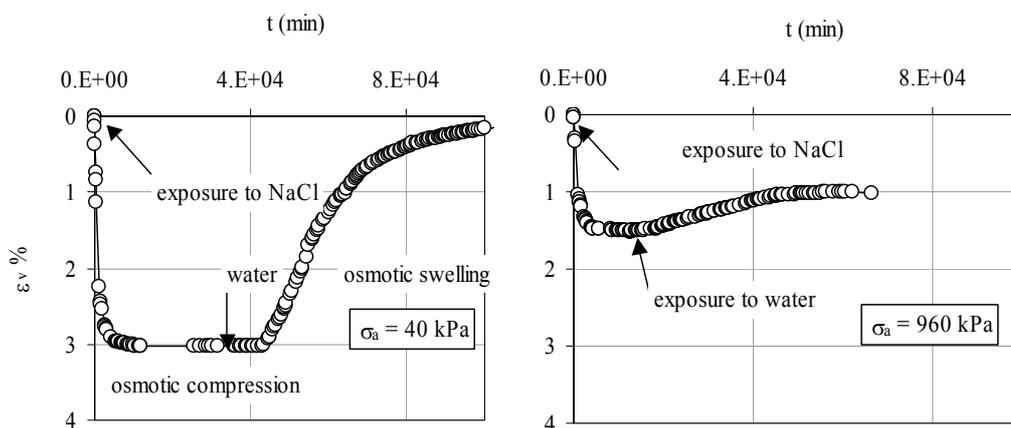


Figure 9. Consolidation caused by exposure to salt solutions and swelling caused by exposure to distilled water of a specimen of the Ponza bentonite reconstituted with distilled water.

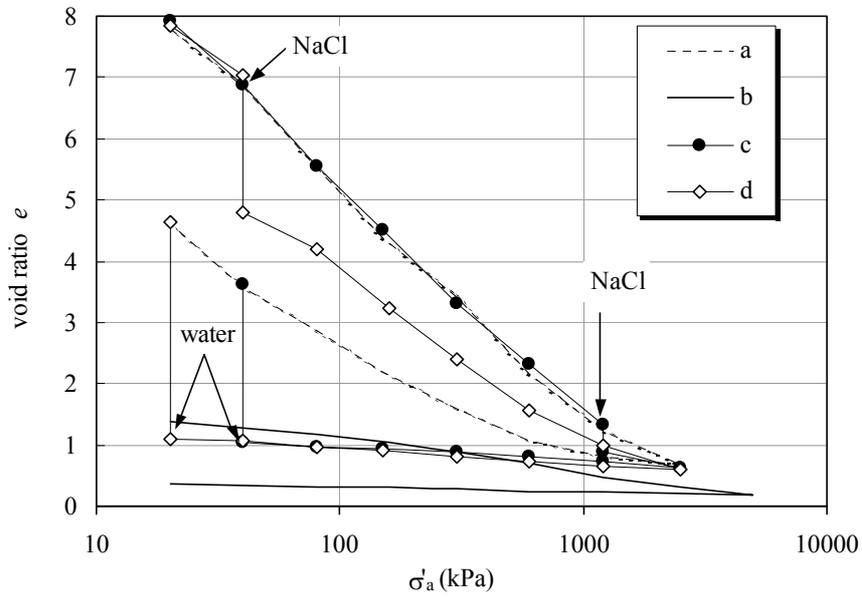


Figure 10. Consolidation caused by exposure to saturated NaCl solution and swelling caused by exposure to distilled water of the Ponza bentonite (Di Maio, 1996).

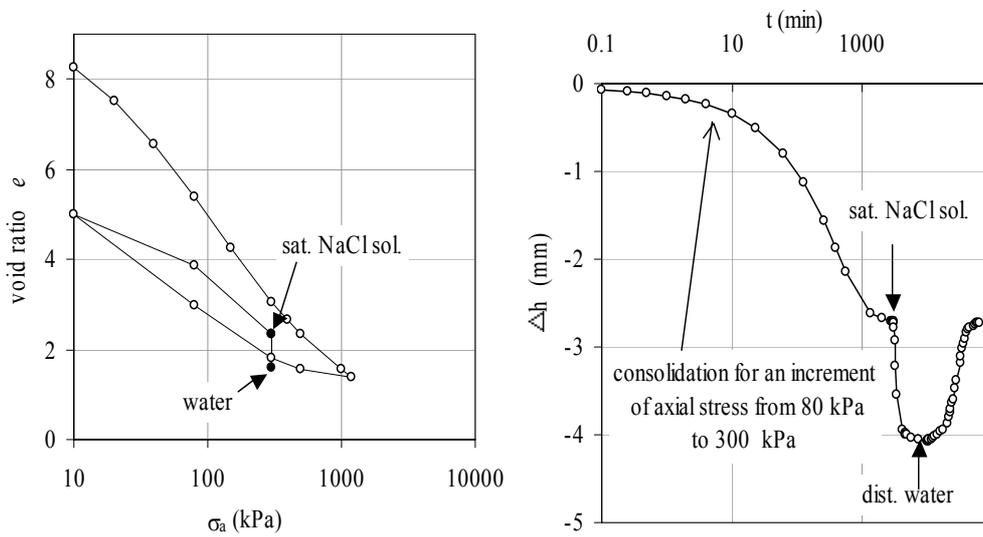


Figure 11. Consolidation caused by exposure to the electrolyte and swelling caused by exposure to water.

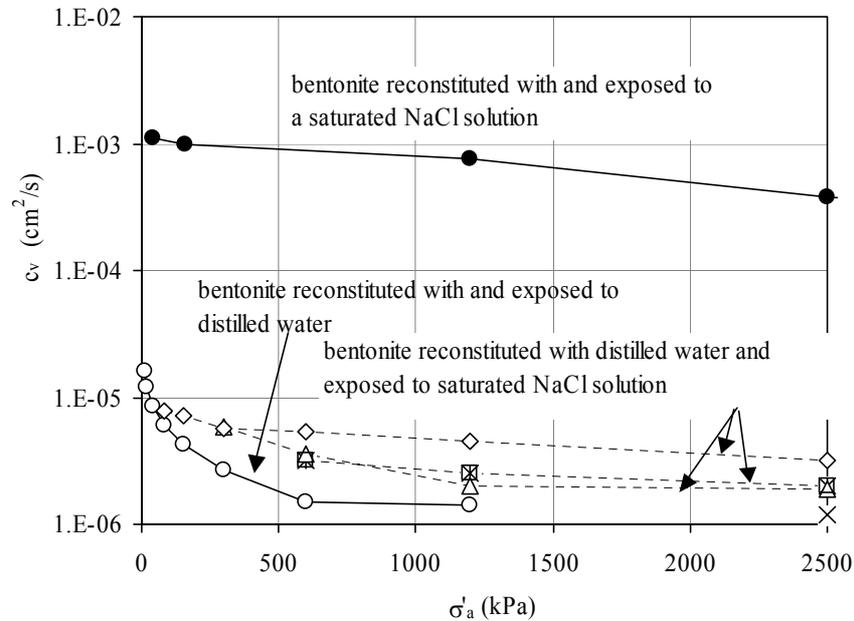


Figure 12. Coefficient of consolidation against axial stress for the Ponza bentonite reconstituted with water or saturated NaCl solution, and for the material reconstituted with water and subsequently exposed to the solution

Exposure to saturated salt solution causes noticeable consolidation, however the equilibrium condition doesn't reach the compression curve of the material prepared directly with the solution, clearly indicating a strong role of initial fabric. The influence of initial fabric is very strong also on the coefficient of consolidation. In fact, the coefficient of consolidation after exposure to the salt solutions is close to that of the material in water and it is very different from that of the material prepared directly with the solution (Figure 12).

3.1.4 Influence of ion concentration. A set of water saturated specimens of the Ponza bentonite was consolidated to 80 kPa and, at the end of mechanical consolidation, each specimen was exposed to a NaCl solution at a given molarity. Figure 13, which reports the results in terms of volumetric strains against the solution molarity, shows that chemical consolidation increases with increasing ion concentration. The largest variations occur in the range 0 – 0.5 M.

After consolidation due to exposure to the salt solutions, the specimens were re-exposed to distilled water. Figure 13 reports the results in terms of absolute values of volumetric strains $|e_s|$ during swelling. The comparison with volumetric strains due to previous consolidation shows that the difference between consolidation and swelling slightly increases with increasing solution molarity.

The influence of ion concentration has been analysed also with reference to HCl solutions. Four specimens of the commercial bentonite were reconstituted with distilled water at the liquid limit, compressed up to 80 kPa while submerged in distilled water. At the end of mechanical

consolidation, three specimens were exposed to HCl solutions at pH = 4; 2 and 0.5 respectively. The solution at pH = 4 did not cause but a slight tendency to swell followed by a negligible consolidation. With pH decreasing, both volume change and rate of consolidation increase (Figure 14). The test relative to pH = 0.5 was interrupted after about 3 days because some iron element of the apparatus started to be corroded. pH = 0.5 corresponds to 0.3 M HCl. The comparison with the consolidation curve obtained for the fourth specimen which was exposed to a 0.3 M NaCl solution shows that, at this molarity, HCl effects are higher than those of NaCl.

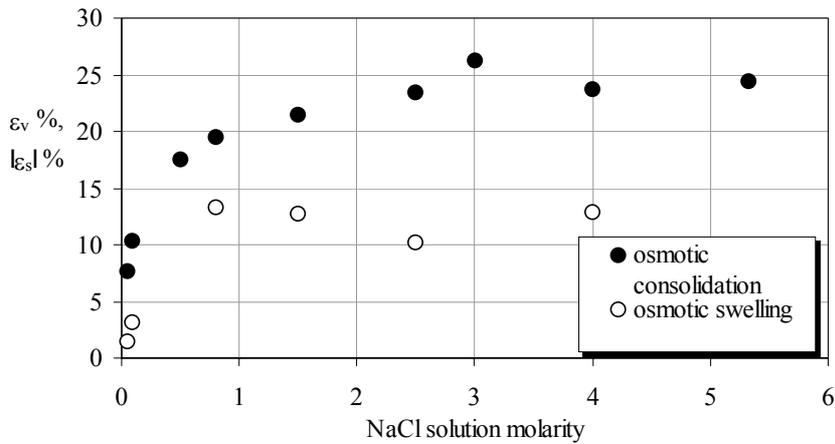


Figure 13. Volumetric strains of the Ponza bentonite caused by exposure to NaCl solutions.

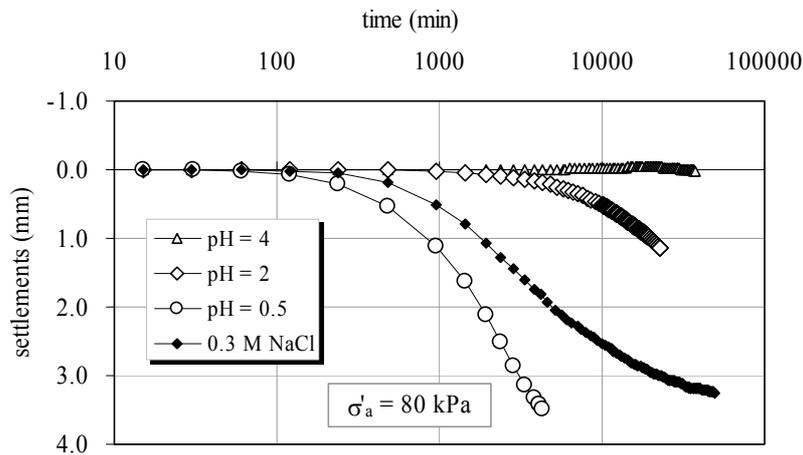


Figure 14. Consolidation of the commercial bentonite caused by HCl solutions at different pH and by 0.3 M NaCl solution.

3.2 Natural soils

Let's consider now the effects produced by exposure to salt solutions of natural soils with a clay fraction lower than that of the Ponza bentonite, with different clay minerals and different types of exchangeable cations.

Some specimens of the considered soils were reconstituted at about the liquid limit with distilled water and, after consolidation at 40 kPa, they were exposed to a saturated NaCl solution, by simply replacing the cell water. Exposure to the electrolyte produced noticeable volume decrease of the Bisaccia and Gela clays (Figure 15); smaller volume decrease for the Marino clay (Figure 16); negligible effects on the Villa d'Agri and Potenza clays (Figure 17) and on the commercial kaolin (Figure 18). At equilibrium, the cell solution was replaced by distilled water. Continuous water renewal produced swelling of the Bisaccia and Gela clays slightly higher than the previous consolidation. In the case of the Marino clay, swelling was much higher than consolidation. So, this specimen was exposed to NaCl solution again and, at the end of consolidation, to distilled water. During this second cycle, consolidation caused by exposure to the electrolyte was higher than in the first cycle and subsequent swelling due to exposure to distilled water was practically equal to the previous consolidation. The Potenza and the Villa d'Agri clays behaved differently from the above materials. They underwent small consolidation after exposure to the salt solution and a larger consolidation after the subsequent exposure to water (Figure 17), as in the case of the commercial kaolin (Figure 18). The behaviour of this latter was similar to that reported by Sridharan and Ventakappa Rao (1973) for a kaolin that was prepared with CCl_4 and that underwent osmotic consolidation because of an inward flow of water, that is, because of an increase in the dielectric constant of the pore fluid.

Once equilibrium after exposure to water was attained, the Bisaccia, Gela and Marino clays were exposed to saturated KCl solution (Figures 15, 16 and 17). This exposure produced a consolidation similar to that previously produced by NaCl. Then the specimens were exposed to distilled water again. The continuous water renewal produced swelling which, as expected, was much smaller than consolidation.

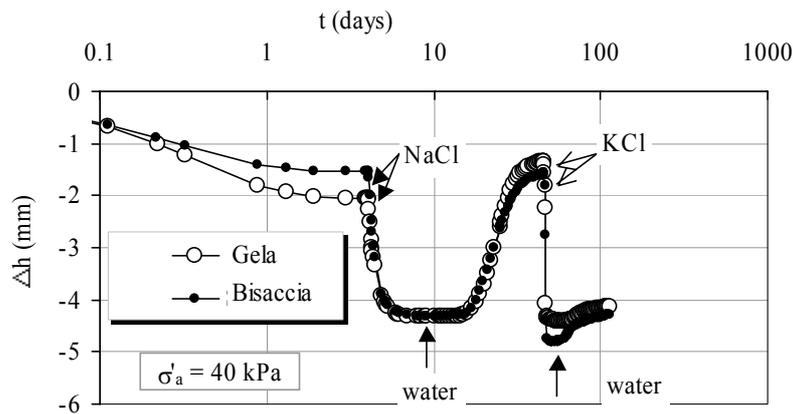


Figure 15. Consolidation of the Bisaccia and Gela clays caused by exposure to saturated NaCl and KCl solutions and swelling caused by exposure to distilled water.

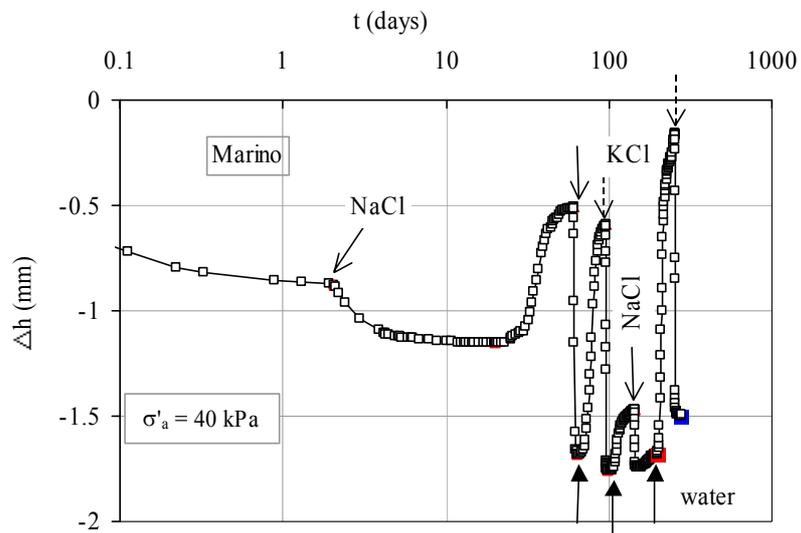


Figure 16. Consolidation of the Marino clay caused by exposure to saturated NaCl and KCl solutions and swelling caused by exposure to distilled water.

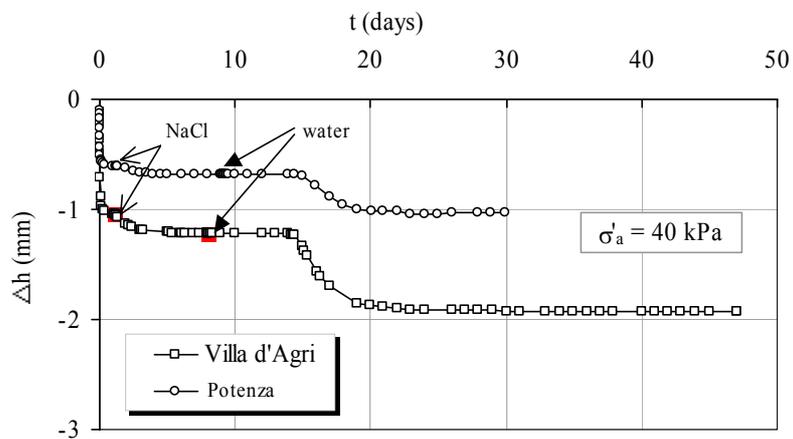


Figure 17. Consolidation of the Potenza and Villa d'Agri clays caused by exposure to saturated NaCl solution and then to distilled water.

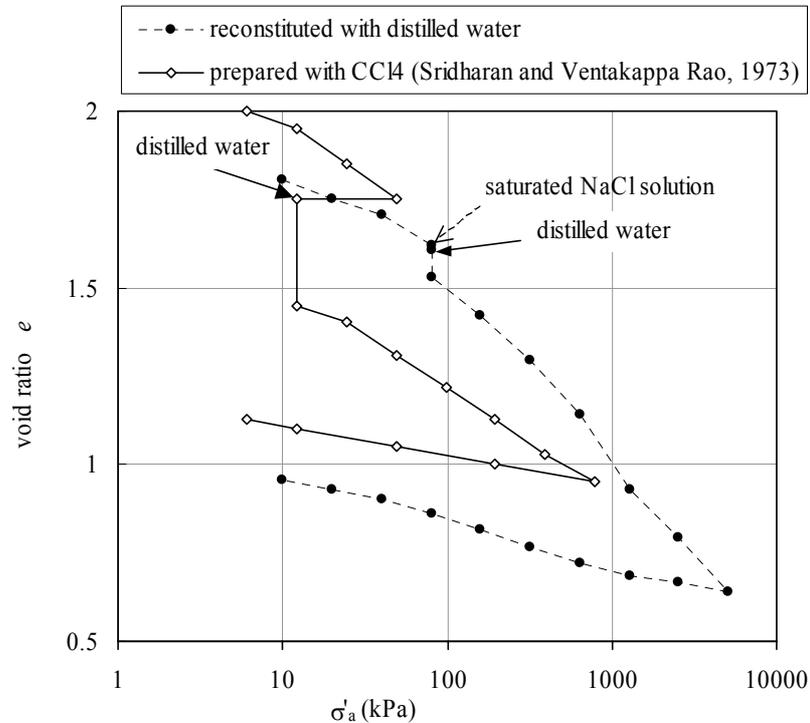


Figure 18. Consolidation of kaolin caused by exposure to saturated NaCl solution and further consolidation due to exposure to distilled water.

Other reconstituted specimens of the Bisaccia and Gela clays were exposed to concentrated salt solutions during normal compression and subsequently to distilled water during unloading. Figure 19 shows the results obtained for two specimens of the Bisaccia clay reconstituted with water at about the liquid limit and initially immersed in water. One of them was tested in the conventional way, the other was consolidated to 40 kPa and subsequently exposed to a saturated NaCl solution. This exposure produced consolidation represented by the straight line normal to the abscissa. In the subsequent compression, the specimen exhibited lower compressibility than the water-saturated specimen. Swelling due to unloading was practically negligible. Once equilibrium at 40 kPa had been reached, the specimen was exposed to water which was continuously renewed: this caused swelling. Subsequent unloading produced further noticeable swelling. Differently from the Ponza bentonite, void ratio after exposure to distilled water of the material which had interacted with the electrolyte was much higher than that of the material which had never interacted with it. Results obtained for other specimens show that the swelling curve subsequent to exposure to distilled water is unique. A series of specimens was reconstituted with 1 M NaCl solution. The specimens were initially compressed while submerged in the same solution, then they were exposed to distilled water under different values of axial stress while in the unloading phase. On subsequent unloading, carried out

during exposure to distilled water, the swelling curves of the different materials were practically coincident (Figure 20).

Figure 21 shows the results relative to the Gela clay exposed to saturated solutions of NaCl and KCl. It can be seen that on re-exposure to distilled water, the specimen which had been previously exposed to NaCl swells much more than the specimen exposed to distilled water for the whole duration of the test. On the contrary, the specimen which had been exposed to KCl swells similarly.

The Marino clay underwent tests slightly different from those carried out on the other clays. Two specimens were prepared with and immersed in distilled water. They were loaded up to 5000 kPa, afterwards, specimen *a* was unloaded conventionally, while specimen *b*, once at equilibrium at 500 kPa, was exposed to a 35g/l NaCl solution (average NaCl concentration in sea water). Such exposure produced negligible consolidation, because of the low values of the actual void ratio. However, it caused a decrease in C_s on subsequent unloading (Figure 22).

Exposure to concentrated salt solutions doesn't always cause consolidation, as shown by Figure 23 relative to the Milazzo soil. The clay underwent small swelling because of exposure to water subsequent to consolidation induced by KCl. However, the subsequent exposure to NaCl produced consolidation first, and then noticeable swelling. As it will be discussed in the 5th paragraph, this behaviour is probably the effect of two processes: counterion substitution and delayed ion diffusion into the intra-aggregates' pores.

The materials prepared with cyclohexane behave very similar to dry materials, and the compression curves of both cyclohexane-saturated and dry materials intersect the normal compression lines of the material reconstituted with aqueous solutions, clearly indicating an increase in shear resistance at the particles' contacts. When a dry material is exposed to an aqueous salt solution, two phenomena can occur simultaneously: hydration of clay particles and double layer formation, and decrease of shearing resistance at particles' contacts. If the first phenomenon prevails, then the material swells. On the contrary, if the latter phenomenon prevails, then the material compresses. In the case of the Bisaccia clay (Figure 24), exposure to a saturated NaCl solution causes swelling if the material is exposed when the condition

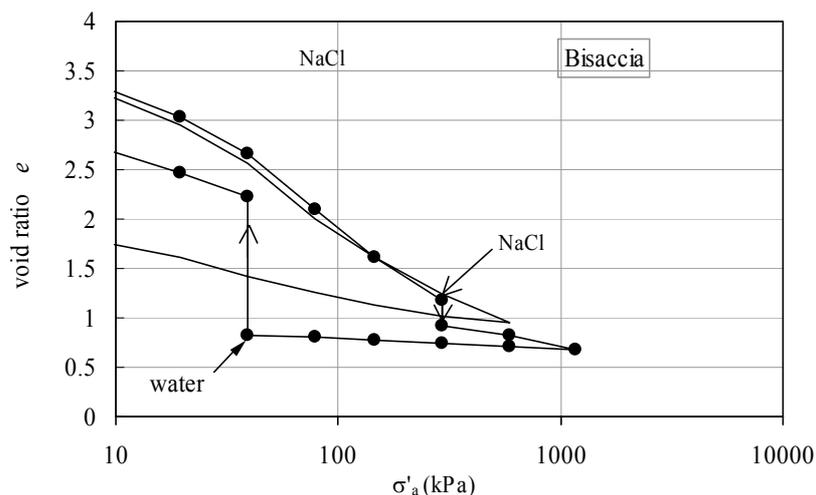


Figure 19. Consolidation of the Bisaccia clay caused by exposure to saturated NaCl solution and swelling caused by exposure to distilled water.

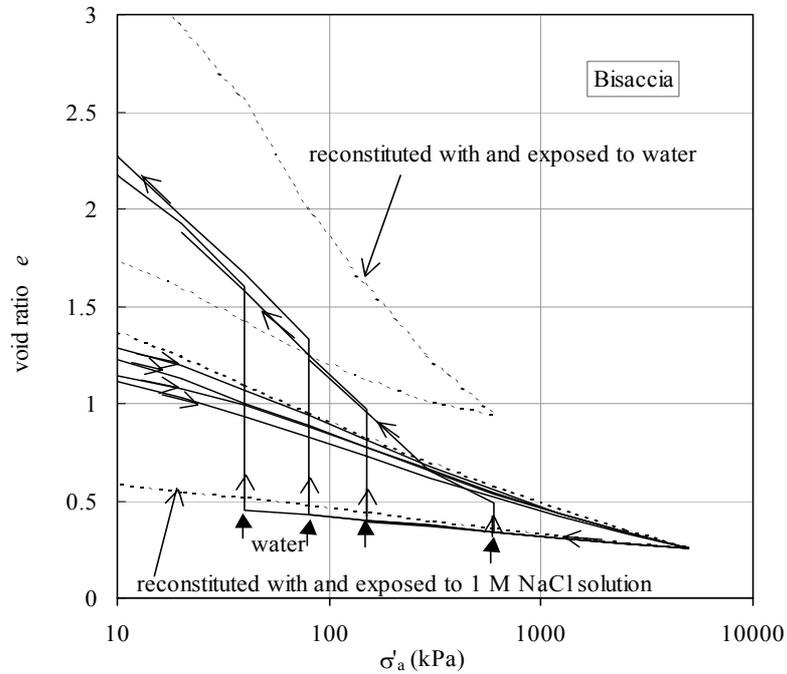


Figure 20. Effects of exposure to distilled water at several different axial stresses on the unload-ding curve of the Bisaccia clay reconstituted with 1 M NaCl solution.

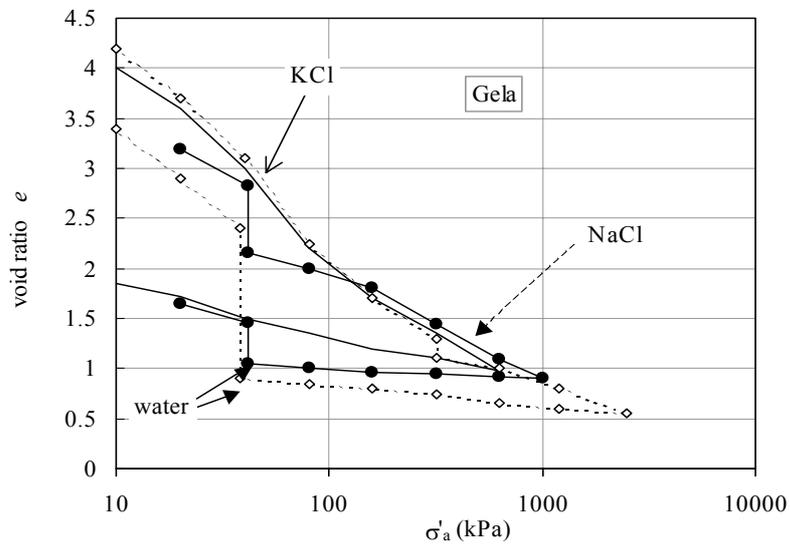


Figure 21. Consolidation caused by exposure to saturated solutions of NaCl and KCl and swelling caused by exposure to distilled water of the Gela clay.

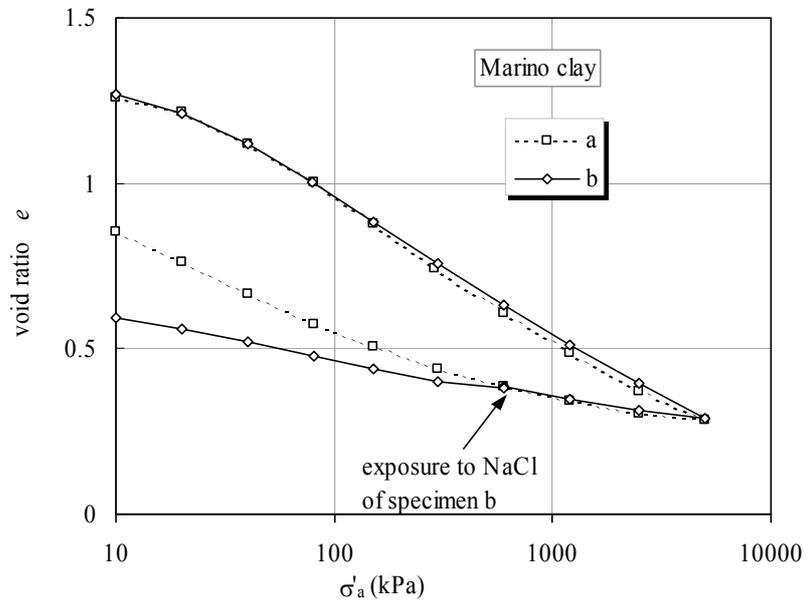


Figure 22. Effects of exposure to a saturated NaCl solution on the swelling behaviour of the Marino clay reconstituted with distilled water.

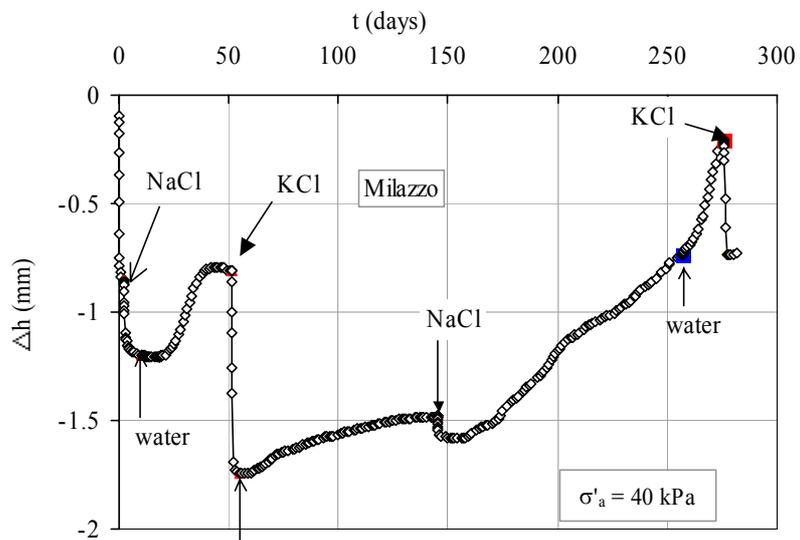


Figure 23. Consolidation of the Milazzo clay caused by exposure to saturated NaCl and KCl solutions and swelling caused by exposure to distilled water and to the NaCl solution.

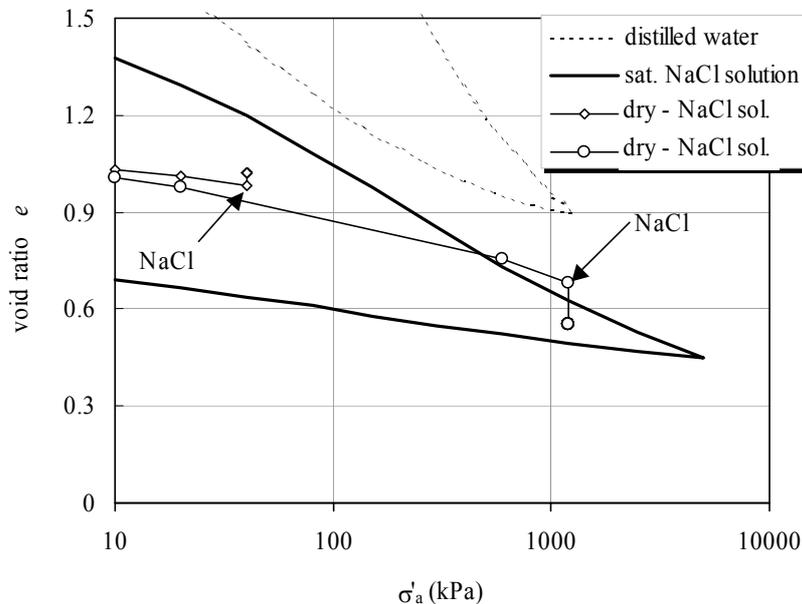


Figure 24. Effects of exposure of dry Bisaccia clay to saturated NaCl solution.

in terms of void ratio and axial stress lies on the left of the intersection. The material consolidates if its conditions before exposure to the solution are on the right of the intersection. So, in this case, the decrease in shearing resistance is the prevailing phenomenon.

3.3 Undisturbed materials

The behaviour of undisturbed materials is greatly influenced by the composition of the fluid to which they are exposed. Figure 25 refers to an undisturbed specimen of the Bisaccia clay. The specimen was immersed in water and was loaded by increments up to 8000 kPa. Afterwards it was exposed to a saturated NaCl solution and, after consolidation, it was exposed to distilled water again, water being continuously renewed. After small swelling, the specimen was unloaded until 1200 kPa (it can be seen that the swelling curve has a trend similar to that obtained for reconstituted specimens and it shows an increase of C_s with OCR). Under an axial stress of 1200 kPa, the specimen was exposed to a saturated NaCl solution (the consequent consolidation is represented by line CD). Afterwards it was unloaded until 600 kPa and, once equilibrium was reached, it was exposed to water, which was continuously renewed. This exposure produced the osmotic swelling represented by the straight line EF. On subsequent unloading, the swelling curve took on the same trend as it had before the exposure to the solution. Under an axial stress of 40 kPa, a noticeable extrusion made it necessary to suspend the test. As in the case of reconstituted specimens, swelling was strongly reduced

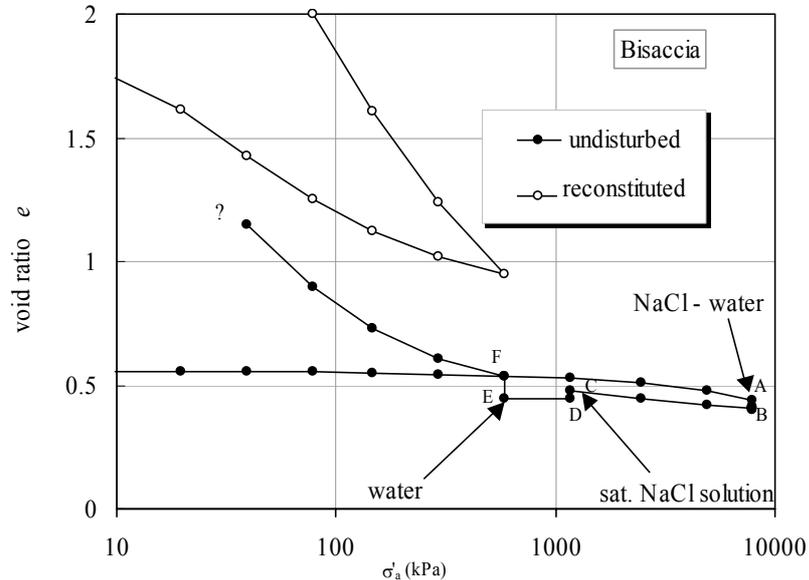


Figure 25. One-dimensional compression and swelling curves of the Bisaccia clay reconstituted with and immersed in distilled water, and of the undisturbed material exposed alternately to distilled water and saturated NaCl solution (Di Maio and Fenelli, 1997).

by exposure to the electrolyte: only the subsequent exposure to water allowed for noticeable swelling.

Figure 26 reports the oedometer curves of two couples of undisturbed specimens of the Bisaccia clay, coming from two different samples: C1, taken at about 2.5 m from the ground level, and C5bis, taken at about 21 m. A specimen of each couple underwent oedometer test in a bath of 1 M NaCl solution, and the other in a bath of distilled water. It can be seen that the specimens exposed to water experienced much higher swelling than those exposed to the NaCl solution. In particular, exposure to distilled water allowed specimen C5bis to reach void ratio close to that of the undisturbed material close to the ground surface. A first simplified analysis of the *in situ* conditions seems to show that the high water content of the upper soil was probably achieved by a similar type of swelling caused by exposure of the marine origin clay to rainwater (Di Maio and Onorati, 2000a; 2000c).

4 Swelling pressure

Swelling pressure was evaluated by means of a continuous swelling equipment which works in strain controlled manner, and by means of conventional oedometers with controlled axial load. Both reconstituted and undisturbed materials were tested (Di Maio, 2001).

Figure 27 reports the results relative to the Bisaccia clay reconstituted with a 1 M NaCl solution and compressed in the triaxial cell to $p'_{max} = 230$ kPa. A specimen was exposed to distilled water in the course of swelling pressure measurement and the other to the salt solution. The figure shows a large difference between the equilibrium values. Furthermore, the time of the process is highly dependent on the composition of both the pore liquid and the

liquid the clay is exposed to. In particular, the time required by the specimen prepared with and exposed to the salt solution is much shorter than that relative to the specimen exposed to water. The procedure used in reconstituting the former specimen was such as to minimise ion exchange and ion diffusion. So, in this case, the time required to reach equilibrium is intrinsic to the process. In the case of the specimen reconstituted with the salt solution and exposed to distilled water, it seems reasonable to hypothesise that the process length is due to slow ion diffusion from the pores to the cell water caused by ion concentration gradients. As ions diffuse, the repulsive interparticle forces increase and, consequently, swelling pressure increases.

The influence of the composition of the liquid the clay is exposed to is even stronger in the case of the undisturbed material, as shown by Figure 28 which reports swelling pressure against time for two undisturbed specimens of a sample taken at a depth of 21 m below ground level. The specimen immersed in a bath of distilled water exhibited a value of swelling pressure as high as 930 kPa. On the contrary, the specimen exposed to 1 M NaCl solution reached a value of about 60 kPa. Under the conditions indicated by the arrow, the cell solution of the latter specimen was substituted with distilled water. This caused a large increase in swelling pressure. It is worth noting that such an increase is due only to variations in physicochemical conditions.

Swelling pressure can be considered as the difference between the osmotic pressure in the central plane between two particles and the osmotic pressure in the equilibrium bulk solution. An equation that allows for the evaluation of osmotic pressure in terms which are convenient for geotechnical purposes was derived for saturated clay by Bolt (1956), under the hypothesis of validity of the Gouy-Chapman model, parallel flat clay particles, validity of van't Hoff's relation.

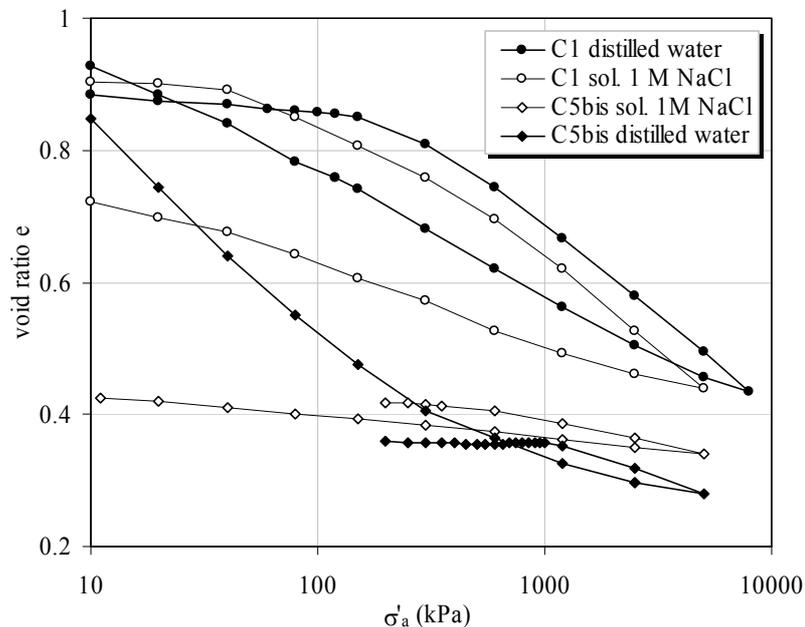


Figure 26. One-dimensional compression and swelling curves of undisturbed Bisaccia clay exposed to a concentrated NaCl solution and to distilled water.

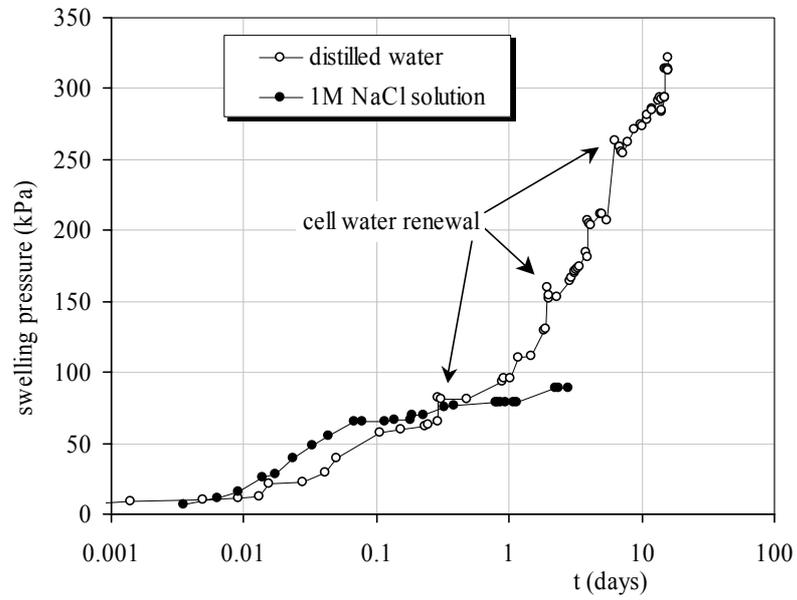


Figure 27. Swelling pressure against time for two specimens of the Bisaccia clay reconstituted with 1 M NaCl solution. A specimen was exposed to the same solution and the other to distilled water.

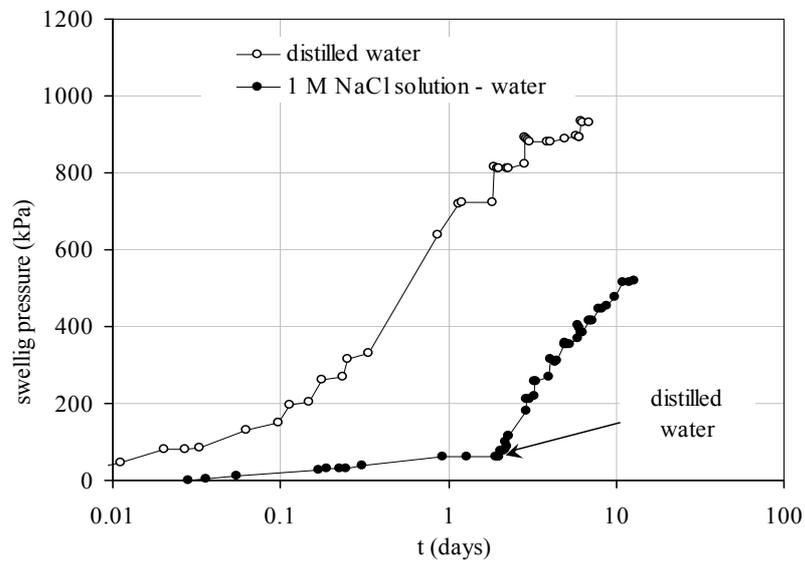


Figure 28. Swelling pressure against time for two undisturbed specimens of the Bisaccia taken at a depth of 21 m below ground level.

It is possible to relate void ratio to swelling pressure, for given values of the other parameters. The solution is highly dependent on A_s . For the considered material, A_s has been evaluated through the empirical relationship found by Farrar and Coleman (1967):

$$w_L = 19 + 0.56 A_s$$

where A_s is expressed in m^2/g . It is worth noting that the values are not very different from those evaluated by an approximate method based on methylene blue adsorption (Di Maio et al. 2003). Figure 29 compares experimental data to theoretical curves. The theoretical curves are relative to 10^{-3} M, and to three values of specific surface. $A_s = 114 \text{ m}^2/\text{g}$ and $A_s = 195 \text{ m}^2/\text{g}$ are, respectively, the minimum and maximum value calculated for the undisturbed samples, and $A_s = 134 \text{ m}^2/\text{g}$ is the value calculated for the reconstituted material. For the other parameters, the following values have been considered: $\nu = 1$, $\beta = 10^{15} \text{ cm/mmole}$; $x_0 = 4/\nu \text{ \AA}$ (valid for montmorillonite); $G_s = 2.73$.

Notwithstanding some exceptions, theory and experiment agree (Figure 29).

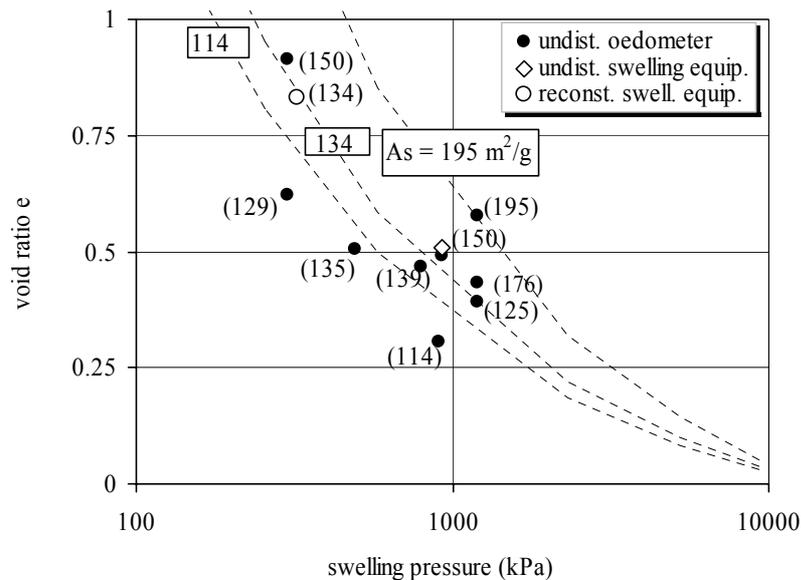


Figure 29. Comparison between experimental results and the double layer model (Di Maio, 2001).

5 Discussion and Conclusions

When a water saturated clay is exposed to a salt solution, depending on the clay porosity, electrolyte concentration and type of ions, it can behave as a semipermeable membrane that allows for the outward flow of solvent but not for the inward diffusion of solute. As described by Mitchell et al. (1973), and Barbour and Fredlund (1989), during the outward flow of water,

negative pore fluid pressures develop within the specimen, and the corresponding increase in effective stresses produces a decrease in volume. Mitchell (1991), while analysing data provided by Farrar and Coleman (1967), and by Barbour and Fredlund (1989), showed that outward osmotic water flow may be significant only in very dense, low-porosity clays and in dilute electrolytes. Conversely, the higher the void ratio and the larger the concentration of the electrolyte, the more important is ion diffusion. The results relative to the Ponza bentonite show that exposure of the water saturated specimens to the three concentrated solutions produced ion diffusion towards the pore fluid. Circumstantial evidence of this is provided by the differences found on re-exposure to water between the effects of KCl and CaCl₂ (irreversible) and those of NaCl (reversible). On re-exposure to water, Na⁺ effects were shown to be reversible; on the contrary, where water substituted CaCl₂ or KCl solutions, the specimens did not undergo that a negligible swelling, even after some months of continuous water renewal.

A diffuse double layer model can explain qualitatively the observed behaviour. According to the classical diffuse double layer theory (Gouy, 1910; Chapman, 1913), the thickness of the double layer increases with ion concentration increasing. The thickness of the double layer decreases also with increasing counterion charge. The Gouy-Chapman model cannot explain the differences between Na⁺ and K⁺ effects because it considers ions as point charges. According to the Stern model (1924), the thickness of the double layer also decreases with decreasing hydrated ion radius. Since the radius of K⁺ is smaller than that of Na⁺, the thickness of a K-montmorillonite double layer is smaller than that of Na-montmorillonite.

Potassium and calcium can be replaced by sodium by exposing the clay to concentrated NaCl solutions, at least at high void ratio and low stress level (Di Maio, 1998). Several processes can account for the observed dependence on stress level, for instance diffusion itself might develop differently. In fact, as the stress level increases, aggregates of particles could form thus creating regions (intra-aggregate pores) where it would be difficult for ions to diffuse.

The behaviour of smectitic clays such as Bisaccia, Gela and Marino clays is mostly qualitatively similar to that of the Ponza bentonite, although the effects are lower because of the lower smectite content. The qualitative differences are fundamentally due to the existence of different types of counterions. For low values of axial stresses, osmotic swelling is higher than osmotic consolidation for two reasons. One reason could be that the clays' pore liquid normally contains a certain amount of ions, although they were prepared with distilled water. During exposure to distilled water these ions are removed together with those which have been made to diffuse into the pore liquid, thus allowing for a larger swelling. The other reason is that, because of its higher concentration, Na⁺ could have replaced other counter-ions, for instance Ca²⁺ and K⁺, thus giving the clay the possibility of a larger swelling as a consequence of exposure to water.

The commercial kaolin and the Potenza and the Villa d'Agri clays behave differently: they undergo small consolidation as an effect of exposure to the salt solution and a large consolidation because of subsequent exposure to water. Since the used kaolin is composed mainly by kaolinite and the other two clays are composed by illite and kaolinite, double layer is a small percentage of their overall water volume. So, a decrease in the double layer thickness caused by exposure to salt solutions doesn't produce noticeable volume changes. Probably, exposure to water makes resistance to particle movements decrease, thus allowing the external loads to work further and to produce porosity reduction. This mechanism was hypothesized by Sridharan and Ventakappa Rao (1973) for a kaolin that was prepared with CCl₄ and that underwent osmotic consolidation because of an inward water flow.

The Milazzo clays underwent small swelling because of exposure to water subsequent to consolidation induced by KCl. However, the subsequent exposure to NaCl produced consoli-

ation first and then noticeable swelling. This behaviour is probably due to the presence of particle aggregates. According to Barbour and Yang (1993), when a clay is exposed to a brine, ions first diffuse into the interaggregate pores. This produces consolidation. Afterwards, when ions diffuse into the intra-aggregates' pores, ion exchange can take place. If Na^+ replaces Ca^{2+} and K^+ , an increase of the double layer thickness can occur.

Results relative to swelling pressure show that the Bisaccia clay is strongly influenced by pore liquid composition and by the composition of the liquid the clay is exposed to. It is interesting to observe that, in the case of reconstituted materials, Bolt's model (1956) interprets satisfactorily the behaviour of the Bisaccia clay reconstituted with a concentrated salt solution and exposed to distilled water. This probably depends on the fact that face-face particle arrangement, which is a hypothesis of the model, is obtained in salt solution for smectite. As expected, the model interprets only qualitatively the behaviour of the material exposed to concentrated salt solutions.

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