INTERNATIONAL CENTRE FOR MECHANICAL SCIENCES

COURSES AND LECTURES - No. 462

# CHEMO-MECHANICAL COUPLINGS IN POROUS MEDIA GEOMECHANICS AND BIOMECHANICS

EDITED BY

BENJAMIN LORET
INSTITUT NATIONAL POLYTECHNIQUE DE GRENOBLE

JACQUES M. HUYGHE
EINDHOVEN UNIVERSITY OF TECHNOLOGY

SpringerWienNewYork

The publication of this volume was co-sponsored and co-financed by the UNESCO Venice Office - Regional Bureau for Science in Europe (ROSTE) and its content corresponds to a CISM Advanced Course supported by the same UNESCO Regional Bureau.

This volume contains 190 illustrations


Printed in Italy
SPIN 10995044

In order to make this volume available as economically and as rapidly as possible the authors' typescripts have been reproduced in their original forms. This method unfortunately has its typographical limitations but it is hoped that they in no way distract the reader.

ISBN 3-211-21323-6 Springer-Verlag Wien New York

# CONTENTS

# Shear Strength of Clays and Clayey Soils: the Influence of Pore Fluid Composition

Caterina Di Maio

Dipartimento di Strutture, Geotecnica, Geologia applicata all'Ingegneria, Università della Basilicata, Italy

**Abstract.** This paper reports experimental results relative to the influence of pore fluid composition on the peak shear strength of the Bisaccia clay and on the residual shear strength of several different clayey soils: the Ponza bentonite, commercial bentonite and kaolin, Bisaccia, Gela and Marino clays. Triaxial tests were carried out on the Bisaccia clay reconstituted with distilled water and with a 1 M NaCl solution. Direct shear and ring shear tests were carried out on dry materials and on the materials reconstituted with distilled water, NaCl solutions at various concentrations, cyclohexane. Some tests were carried out by using KCl solutions, ethanol and ethylene glycol. The results show that pore fluid composition influences greatly both the peak and residual shear strength of smectitic soils, even when the clay fraction is very low. The residual friction angle is about 5° in distilled water, 15° in concentrated NaCl solution, and varies between 30° and 35° for materials dry or prepared with cyclohexane. The residual friction angle is strongly correlated to the static dielectric constant of the pore fluid.

## 1 Introduction

Shear strength of pure clays is strongly influenced by pore fluid composition (among others: Kenney, 1967; Mesri and Olson, 1970; Sridharan, 1991; Mitchell, 1993, Di Maio, 1996a, 1996b). Furthermore shear strength of natural soils depends on clay fraction and clay composition. In particular, soils with clay fraction c.f. > 50% exhibit values of the residual shear strength equal to those of their clay part (Lupini et al., 1981). For 25%<c.f.<50% results are extremely scattered and strongly influenced by mineral and pore fluid composition. If the clay component is constituted by minerals with high specific surface such as montmorillonite, and the pore fluid is constituted by distilled water, then 25% - 30% c.f. is sufficient to make the residual strength of a composite soil equal to that of its clay part (Di Maio and Fenelli, 1994). Di Maio (1996a) reported data relative to some natural clays containing different percentages of montmorillonite, reconstituted with distilled water and with saturated NaCl solution, showing that the clays exhibit almost the same values of residual shear strength as the Ponza bentonite - which is a practically pure montmorillonite - both in distilled water and in the salt solution.

Natural state pore fluid is often a compound solution, hence the use of distilled water for laboratory tests would be not appropriate. Anson and Hawkins (1998) briefly discussed the implication for slope stability analysis of using deionised 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 deionised water. Besides its practical importance, an analysis of the influence of pore fluid composition on shear strength is very important for the elucidation of the shearing mechanism.

Generally, in the study of the influence of pore fluid composition on the behaviour of the different types of soils, the effects of ionic aqueous solutions and those of organic solvents are analysed separately. The purpose of this paper is to systematically examine shear strength response of different soils at pore fluid variations, comparing the influence of "extreme" types of pore fluids: water, salt solutions at various concentrations, organic solvents with different dielectric constants and air.

## 2 Materials and Methods

The experimentation was carried out on the Ponza bentonite, Bisaccia, Gela and Marino clays, a commercial kaolin provided by Igma srl (Sassuolo, Italy) and a commercial bentonite provided by Laviosa Chimica Mineraria SpA (Livorno, Italy). Particle size distribution curves of the tested soils are reported by the companion papers on this volume. The same papers report mineral composition, liquid limit evaluated by mixing the soils with NaCl solutions at various concentrations, the liquid limit of the Ponza and Bisaccia clays evaluated also with cyclohexane, ethanol and dimethylsulfoxide. The liquid limit of the commercial bentonite was evaluated with different solutions including HCl solutions at various pH.

Peak shear strength was evaluated by means of common triaxial CU tests carried out on normally consolidated specimens of the Bisaccia clay reconstituted with distilled water and with 1 M NaCl solution. The tests were carried out with constant cell pressure and with the axial stress increased in a strain controlled manner, at a rate of 0.03 mm/min.

Residual shear strength was determined by use of the conventional Casagrande box and by the Bishop ring shear apparatus. In the first case, for each value of axial stress, the specimens were sheared back and forth until the minimum strength was obtained. For both cases, rates of displacement in the range 0.001 – 0.005 were adopted. Various pore fluids were used: water, salt solutions at various concentrations and three organic solvents: cyclohexane, ethanol and ethylene glycol. Dry materials were also tested.

## 3 Results

### 3.1 Shear strength of normally consolidated Bisaccia clay

The influence of pore fluid composition on the peak strength value of normally consolidated material was determined only for the Bisaccia clay. It is known that the intrinsic compression line of this material is strongly dependent on the pore liquid composition. Figure 1 reports the one-dimensional curves of void ratio against effective axial stress for the material reconstituted with and exposed to distilled water and for the material reconstituted with and exposed to a 1 M NaCl solution. Points $A^I$ represent the equilibrium conditions after isotropic normal consolidation for three water-saturated specimens, and points $B^I$ for solution-saturated specimens. These specimens underwent CU tests. The results of the tests, in terms of $q' = \sigma'_a - \sigma'_r$ against $p' = (\sigma'_a + 2\sigma'_r)/3$, show that the specimens reconstituted with the salt solution are characterised by much higher values of shear strength than the specimens reconstituted with distilled water (Figure 2).

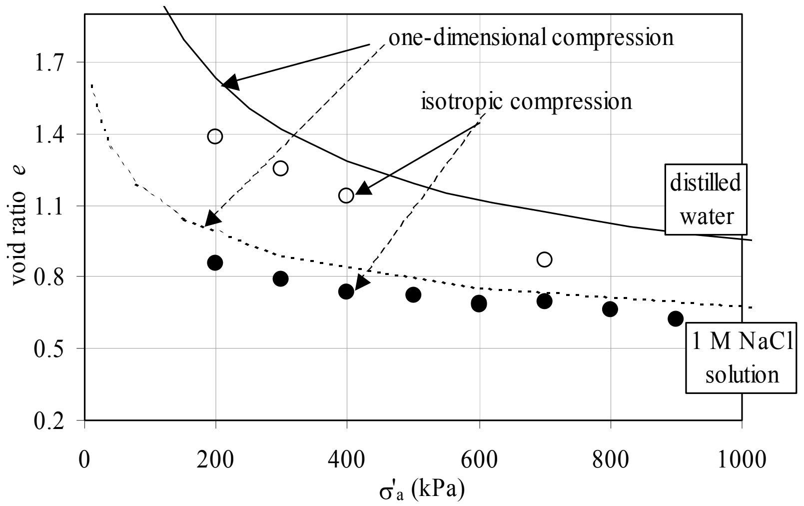


**Figure 1.** Intrinsic one-dimensional compression lines of the Bisaccia clay reconstituted with water and with a 1 M NaCl solution, and isotropic compression points of specimens which underwent triaxial tests.

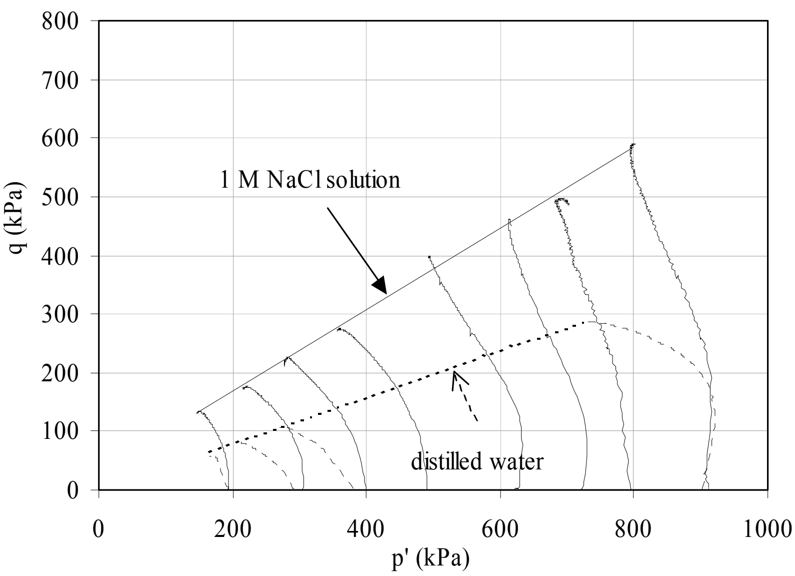


**Figure 2.** CU triaxial tests on normally consolidated specimens of the Bisaccia clay.

Other tests were carried out in order to evaluate the influence on shear strength of the type of test and of the composition of the fluid of the hydraulic circuits. Figure 3 compares the results of CU tests to those of CD tests carried out on specimens reconstituted with 1 M NaCl solution. The hydraulic circuits of the triaxial cell and the porous stones were saturated with distilled water. It can be observed that shear strength determined by CU tests is higher than that determined by CD tests. It is reasonable to hypothesise that, in the case of the CD test, ions of the pore solution could have diffused towards external water, so making shear strength decrease. This process could not occur in the case of the CU test. As a matter of fact, when the hydraulic circuits of the triaxial cell and the porous stones are saturated with the same solution as the pore solution, the differences between the two types of tests decrease greatly, as shown by Figure 4 which compares the results of CU and CD tests which were carried out by saturating circuits and porous stones with a 1 M NaCl solution. The specimens, reconstituted with the same solution, were consolidated to 800 kPa, and afterwards each of them was unloaded to a given value of *p'*. At equilibrium, some specimens were sheared in drained conditions, with a rate of axial displacement of 0.0015 mm/min, and some others in undrained conditions at a rate of 0.03 mm/min. It can be observed that, in this case, the two types of tests furnish similar results.

Peak values of strength are influenced by the different initial void ratios of the material reconstituted with the two different fluids. In order to minimize the influence of initial fabric, it is convenient to refer to the residual shear strength which is known to be independent of it.

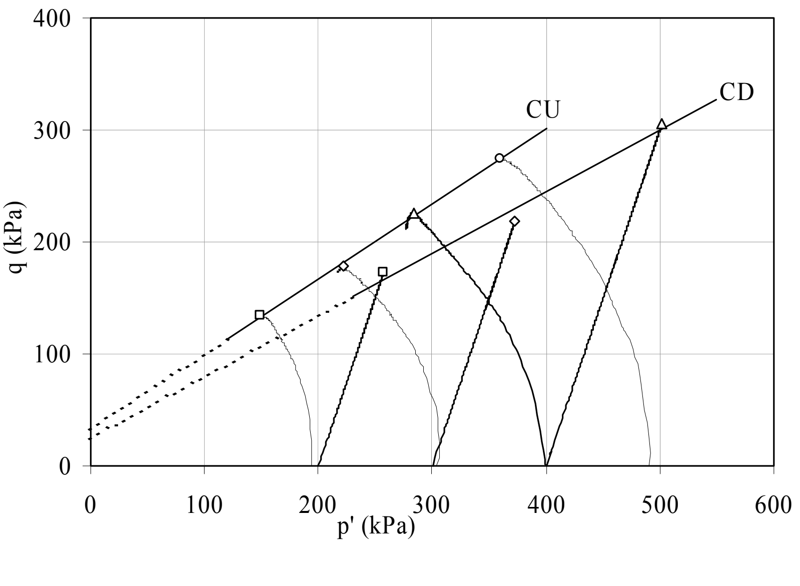


**Figure 3.** Results of CU and CD triaxial tests carried out on normally consolidated Bisaccia clay exposed to distilled water (Di Maio and Onorati, 2000b).

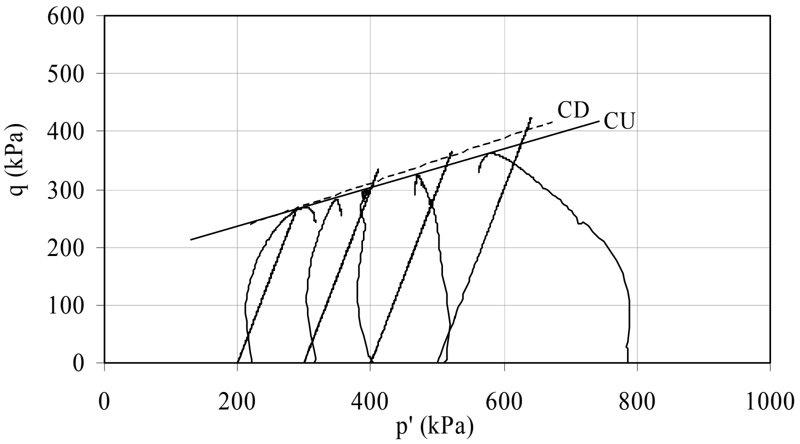


**Figure 4.** Results of CU and CD tests on the Bisaccia clay reconstituted with and exposed to 1 M NaCl solution (Di Maio and Onorati, 2000b).

### 3.2 Residual shear strength

The materials were reconstituted with distilled water and initially sheared while immersed in distilled water. In these conditions, the residual shear strength of all the considered materials was found to be very close to that of the Ponza bentonite and lower than that of the commercial kaolin (Figure 5). Once the residual shear strength had been reached, the cell water was replaced by a saturated NaCl solution. This replacement did not cause any effect on kaolin behaviour, whereas it caused a strong increase in the other soils' shear strength. In particular, the Bisaccia and Gela clays residual shear strengths are close to that of the Ponza bentonite, whereas the Marino clay strength is close to that of the commercial kaolin. It seems reasonable to hypothesise that the Marino clay behaviour depends on its low smectite content (about 10% in dry weight). When the pore fluid is distilled water, the volume of the smectite component is sufficient to influence shear strength, whereas, in the case of the concentrated salt solution, the smectite volume decreases greatly and kaolinite particles probably interact directly.

For all the considered soils, the residual shear strength obtained after exposure of water saturated materials to a saturated salt solution is equal to that obtained for the materials prepared directly with the solution and submerged in it (Di Maio, 1996a; 1996b).

The influence of NaCl solution concentration on residual shear strength was determined on specimens reconstituted with NaCl solutions at given concentrations and exposed to the same solutions. The results show that as ion concentration increases, residual shear strength of smectitic soils increases (Figure 6). The largest variations occur in the range 0 - 0.5 M, and only negligible variations occur between 0.5 M and saturation. It is worth noting that the point at 0.1 M in Figure 6 was obtained for a specimen of the Bisaccia clay reconstituted with a solution similar to the natural pore solution which had been previously analysed. The corresponding shear strength, although much lower than the maximum, is higher than that obtained with distilled water.

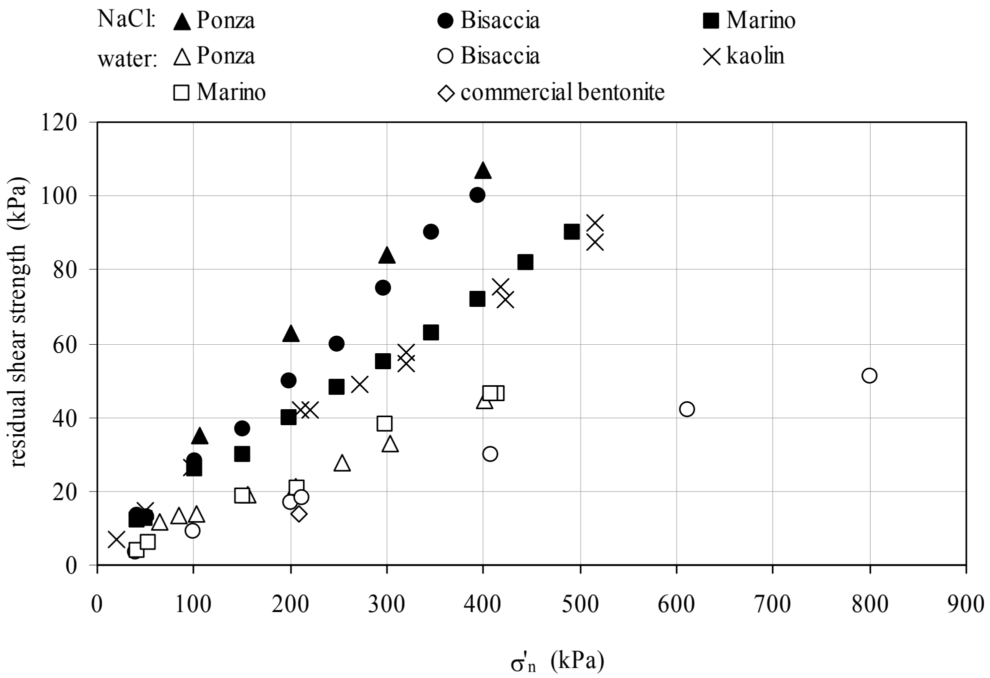


**Figure 5.** Residual shear strength against normal stress for the materials prepared with and exposed to distilled water and for the same materials after exposure to a saturated NaCl solution (Di Maio, 1996a).

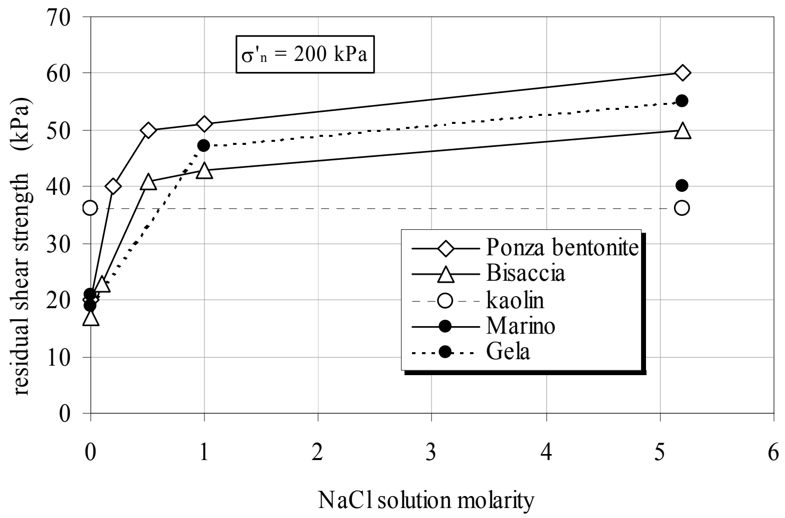


**Figure 6.** Residual shear strength under $\sigma'_n$ = 200 kPa against NaCl solution molarity.

KCl effects on the residual shear strength of the considered materials are slightly higher than those exerted by NaCl, as shown by Figure 7 for the Bisaccia clay. Also the results relative to the Ponza bentonite show that the effects of $K^+$ are slightly higher than those of $Na^+$ (Di Maio, 1996b).

Although the residual shear strength of smectitic soils increases dramatically as ion concentration increases, it is much lower than that the materials can exhibit with other pore fluids. This is shown by further experimental results of direct shear tests and ring shear tests carried out on dry materials and on the materials prepared with, and exposed to, organic fluids with low dielectric constants. Testing is very difficult in these conditions and results rather dispersed. Apparently, the irregularity of the shear surface is one of the main causes of the dispersion. So, often the tests were interrupted and 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 regular planar surface were considered in the analysis. Figure 8 reports the results obtained for a specimen of the dry Bisaccia clay tested in the Bishop ring shear apparatus under three different values of normal stress, at a rate of 0.001 mm/min. In the course of the test, the specimen was exposed to ethanol and sheared further. The exposure caused a noticeable decrease in strength with respect to the dry material.
This latter, in turn, behaved very similarly to the material prepared with and immersed in a non polar organic fluid, cyclohexane, whose dielectric constant D=2 is very close to that of air. The cohesion intercept being null, it is possible to interpret the results in terms of residual friction angle $\varphi'_r$ . The strength parameter is about 30° for the Bisaccia clay prepared with cyclohexane or dry, about 24° for the material prepared with ethanol, 15° for the material reconstituted with 1 M NaCl solution, about 5° in water!

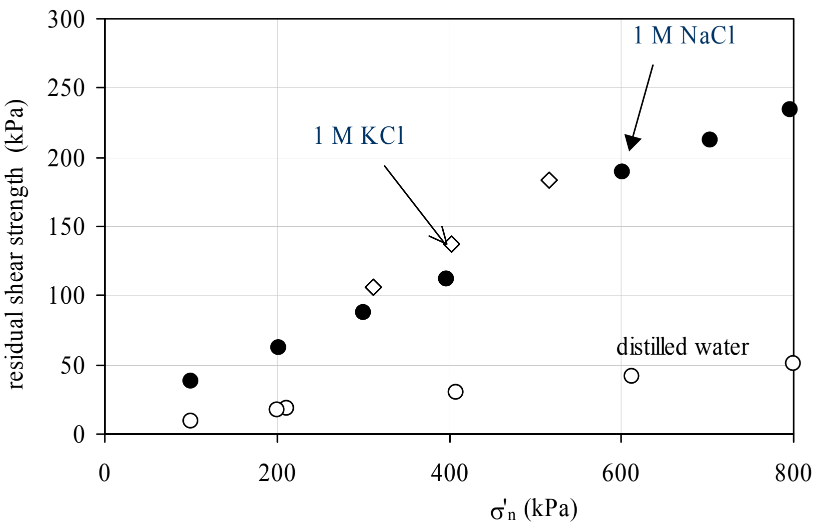


**Figure 7.** Residual shear strength against axial stress for the Bisaccia clay reconstituted with water, 1 M NaCl and 1 M KCl solutions.

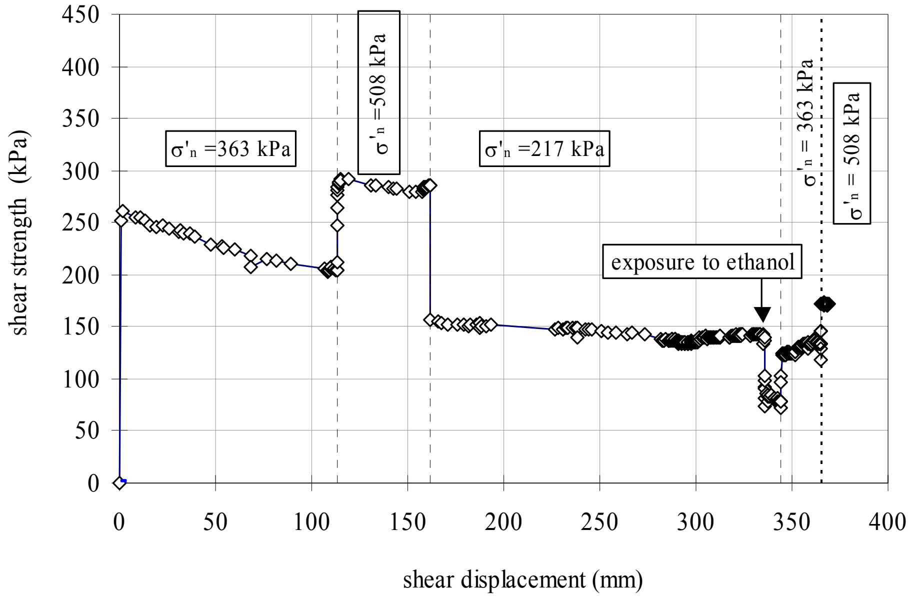


**Figure 8.** Shear strength against shear displacement for a dry specimen of the Bisaccia clay which was exposed to ethanol in the course of the test.

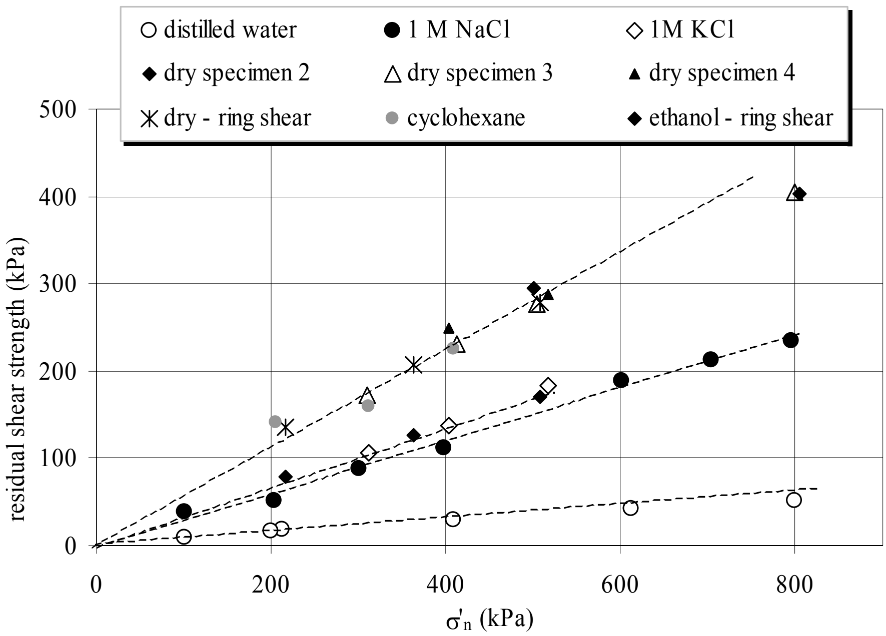


**Figure 9.** Residual shear strength against normal stress for the Bisaccia clay with different pore fluids.

An analogous experimentation was carried out on the Ponza bentonite. The results show that the influence of pore fluid composition is very similar to that observed on the Bisaccia clay (Figure 10).

The increase in strength caused by an increase in pore solution concentration probably depends also on the lower void ratio of the materials prepared with the electrolyte. Under the considered stress level, void ratio of the material, either dry or in cyclohexane, is equal or higher than that in the saturated salt solution. So, the increase in shear strength reasonably depends on a particular particle aggregation or on an increase in shear resistance at the particles' contacts. Such an increase can be caused by an increase in electrodynamic attraction forces. These forces are complex functions of the dielectric constant of the pore fluid as well as of the solid skeleton. The dielectric constant, in turn, is a function of the frequency of electromagnetic fluctuations. However, to a first approximate analysis, all data can be analysed with reference to the pore fluid static dielectric constant. Figure 11, shows that the ratio $\tau_r/\sigma'_n$ decreases with pore fluid static dielectric constant increasing. The figure reports also the result relative to the Bisaccia clay exposed to ethylene glycol. It can be observed that this result is consistent with the others in terms of dielectric constant.

In this first experimentation, both aqueous ion solutions and organic solvents were used for D < 75 and the results relative to the two types of fluids seem to be comparable. However, only aqueous ion solutions were used for D higher than about 75. Further experimentation is now under consideration with organic fluids with D > 75 in order to understand whether the results relative to organic fluids can be compared to those of salt solutions also when these latter are dilute.

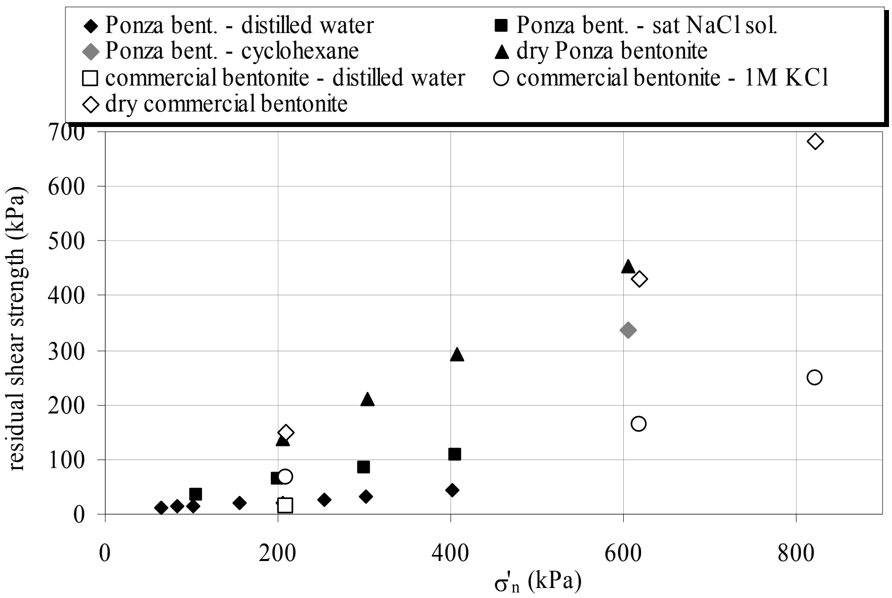


**Figure 10.** Residual shear strength against normal stress for the Ponza bentonite and the commercial bentonite prepared with different types of pore fluid.

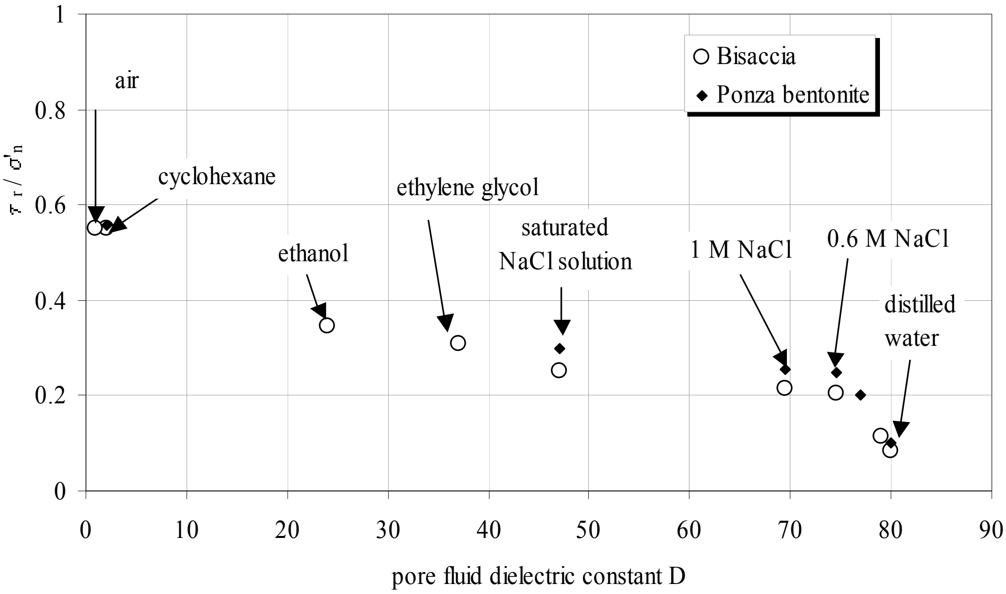


**Figure 11.** Ratio $\tau_r/\sigma'_n$ against pore fluid static dielectric constant for the Bisaccia and the Ponza clays prepared with different types of pore fluid.

## 4 Conclusions

This paper compares the influence of "extreme" types of pore fluids: water, concentrated salt solutions, organic solvents and air on several different soils. The results show that, with the exception of the used kaolin, the other considered soils are noticeably influenced by pore fluid composition. It is worth noting that soils containing small smectite percentages, such as the Marino clay, exhibit the same residual shear strength as the Ponza bentonite which is a practically pure montmorillonite.

The residual friction angle of smectitic soils is about 5° in distilled water, 15° in concentrated NaCl solution, and varies between 30° and 35° for materials dry or prepared with cyclohexane. Furthermore, it is strongly correlated to the static dielectric constant of the pore fluid.

Pore fluid in nature is generally a dilute composite solution. The results reported in this paper show that the largest variations of the residual shear strength of smectitic soils prepared with NaCl solutions occur in the range 0 – 0.5 M. In particular, the residual shear strength evaluated on the Bisaccia clay prepared with a solution similar to its natural pore solution is noticeably higher than that obtained with distilled water.

Most of the clays we deal with formed in marine environment. In order to understand their behaviour, it is important to take into account their original intrinsic properties which can be only determined by using concentrated salt solutions. For instance, the comparison between results obtained by using distilled water and those obtained by using concentrated NaCl solutions gives an idea of the variations which would have occurred - and that can still occur - in marine origin clays as an effect of exposure to rainwater (Di Maio and Onorati, 2000a; 2000b; 2000c).


**Acknowledgements**

The Author would like to thank Dr. Rossella Coviello for her help in carrying out some of the tests.


**References**


Anandarajah, A., and Zhao, D. (2000). Triaxial Behavior of Kaolinite in Different Pore Fluids. *J. of Geotechnical and GeoEnvironmental Engineering*, 126, n. 2, p. 148 – 156.

Anson, R. W. W., and Hawkins, A. B. (1998). The effect of calcium ions in pore water on the residual shear strength of kaolinite and sodium montmorillonite. *Géotechnique*, vol. XLVIII, n. 6, pp. 787 - 800.

Di Maio, C., and Fenelli, G.B. (1994). Residual strength of kaolin and bentonite: the influence of their constituent pore fluid. *Géotechnique*, vol. XLIV, n. 2, pp. 217 - 226.

Di Maio, C. (1996a). The influence of pore fluid composition on the residual shear strength of some natural clayey soils. *VII International Symposium on Landslides*, vol. II, pp. 1189 -1194.

Di Maio, C. (1996b). Exposure of bentonite to salt solution: osmotic and mechanical effects. *Géotechnique*, vol. XLVI, n. 4, pp. 695 - 707.

Di Maio, C., and Onorati, R. (2000a). Swelling behaviour of active clays: the case of an overconsolidated, marine origin clay. *Proceedings of the VIII International Symposium on landslide*, Cardiff, Vol. 1, 469 – 474.

Di Maio, C., and Onorati, R. (2000b). Influence of pore liquid composition on the shear strength of an active clay. *Proceedings of the VIII International Symposium on landslide,* Cardiff, Vol. 1, 463 – 468.

Di Maio, C., and Onorati, R. (2000c). Osmotic softening of overconsolidated clays. *Proceedings of the International Conference on Geotechnical & Geological Engineering*, Melbourne.

Kenney, T. C. (1967). The influence of mineralogical composition on the residual strength of natural soils. *Proc. Geotech. Conf. on Shear Properties of Natural Soils and Rocks*, Oslo, vol.I, pp. 123-129.

Lupini, J. F., Skinner, A. E., and Vaughan, P. R. (1981). The drained residual shear strength of cohesive soils. *Géotechnique* 31, No.2, pp. 181-213.

Mesri, G., and Olson, R. E. (1970). Shear strength of montmorillonite. *Géotechnique*, vol. XX, n. 3, pp. 261-270.

Mitchell, J. K. (1993). Fundamentals of soil behaviour. 2nd ed. John Wiley & Sons, Inc.

Moore, C. A., and Mitchell, J.K. (1974). Electromagnetic forces and soil strength. *Géotechnique*, vol. XXIV, n.4, pp. 627 – 640.

Sridharan, A. (1991). Engineering behaviour of fine grained soils. *Indian Geotechnical Journal*, vol. XXI, n. 1, pp. 1-136