



UNIVERSITÀ  
DEGLI STUDI  
FIRENZE

# FLORE

## Repository istituzionale dell'Università degli Studi di Firenze

### **Mechanical proprieties of a sodicated soil**

Questa è la Versione finale referata (Post print/Accepted manuscript) della seguente pubblicazione:

*Original Citation:*

Mechanical proprieties of a sodicated soil / P. SPUGNOLI; E. MELANI. - In: RIVISTA DI INGEGNERIA AGRARIA. - ISSN 0304-0593. - STAMPA. - 4:(2005), pp. 1-10.

*Availability:*

This version is available at: 2158/223316 since:

*Terms of use:*

Open Access

La pubblicazione è resa disponibile sotto le norme e i termini della licenza di deposito, secondo quanto stabilito dalla Policy per l'accesso aperto dell'Università degli Studi di Firenze (<https://www.sba.unifi.it/upload/policy-oa-2016-1.pdf>)

*Publisher copyright claim:*

(Article begins on next page)

# MECHANICAL PROPERTIES OF A SODICATED SOIL

Paolo Spagnoli, Miguel Melani Esteban

## 1. Foreword

The use of brackish water for irrigation is a world wide well known problem: it implies an excess of the Na cation in soil whose negative effects are either on plant physiology than on soil structure degradation [19]. Its major evidence is the hardening of dispersive soils and the crusting and sealing in the surface horizon, as well as important variations on their mechanical properties [8].

The negative action of Na on the soil structure, compared with that of other cations, namely Ca, Mg and K, has been investigated by many authors [16; 1; 3].

The increasing of clay dispersion, caused by greater SAR (Sodium Adsorption Ratio), apart of other negative effects, also results in a higher mechanical strength of soil and aggregates as it was demonstrated by A. R. Barzegar et al [1] and M. A. Taboada and R. S. Lavado [21]. Their works focused on the assessment of tensile strength either by the measure of single aggregate rupture force or by the brazilian test. In both cases samples were at air moisture and for the brazilian test they were formed with remoulded and drayed soil. However, mechanical strength alone gives poor information regarding stress-strain relationships and their repercussion on soil tillage and traffic problems. To relate soil volumetric change in response to external loads, a suitable approach is that of critical state soil mechanics [6; 13; 9]. Its main parameters may be determined by compression and direct shear tests together with the measure of samples height variation during shear [10]. Furthermore, direct shear test allow the assessment of Coulomb soil strength parameters as well [23].

The wetting-drying cycles and the associated swelling and contraction of clay, strongly affect ag-

gregates stability and formation which reflects on soil mechanical properties [22; 2; 18], particularly for sodic soil [17].

The present work is part of a wider research project involving several research groups aimed to analyze the effects on agricultural soils of the use of brackish water. Recent researches carried out within the project detected only minor if not insignificant effects of sodicity levels on cone-index values and Atterberg limits [5] and as regard structure stability, sodicity effects were clearly manifested only for ESP values higher than 5 [3].

The paper reports the results of a study aimed to analyze the changes in mechanical behaviour of an agricultural soil at two different levels of sodicity by way of critical state theory and Coulomb-law parameters.

## 2. Materials and methods

### *The theory*

The critical state theory developed by Roscoe at the University of Cambridge and later adapted by Hettiaratchi has been since utilized by many authors to characterize the mechanical behaviour of agricultural soils [12; 20; 4; 14].

The theory is a powerful tool to explain soil deformations within a wide range of conditions [11]. It allows to represent all the possible stress-strain soil states in the three dimensional space of coordinates  $p - q - v$ , where  $p$  is the normal stress,  $q$  the shear stress and  $v$  the specific volume. Increasing shear stress the soil deformation path reaches a so-called critical state at which soil flows without any change of volume as well as  $p$  and  $q$ . The possible soil states loci are delimited by the boundary surfaces, namely the Roscoe, Hvorslev and Tension Surfaces (see Fig. 1a). The interception of the Roscoe and Hvorslev surfaces represents the critical state line (CSL), while the interception of Roscoe surface with  $q=0$  plane is the normal consolidation line (NCL) and represents the variation of the specific volume during isotropic compression (see fig1b). The imaginary vertical wall obtained projecting the CSL on the  $q=0$  plane divides the space for a given

---

Memoria presentata il 18.11.04; accettata il 19.01.05

Prof. Ing. PAOLO SPAGNOLI; DIAF, Università degli Studi di Firenze, P.le Cascine, 15 - 50144 Firenze, Italy. Fax 39 055 3288316, (paolo.spagnoli@unifi.it)

Ing. ESTEBAN M. MELANI; DIAF, Università degli Studi di Firenze, P.le Cascine, 15 - 50144 Firenze, Italy, (emmelani75@hotmail.com).

soil at given moisture conditions in two sections, called super-critical and sub-critical domain. Starting from a point in the super-critical domain, any applications of a deviatoric stress  $q$  will result in a volume increase until the soil reaches the CSL at failure. Conversely, by starting from a sub-critical condition, the deformation will bring to a volumetric decrease (compression). It is evident that for an agricultural soil the results are totally different. The projection of the CSL on the  $q=0$  plane discriminates super-critical and sub-critical state in terms of  $p$ - $v$  combinations. On the same plane, CSL and NCL are represented in a  $v$ - $\ln(p)$  semi logarithmic graph by two parallel straight lines (as reported by Hettiaratchi [7]), defined by the equations:

$$\text{CSL: } v = \Gamma - \lambda \cdot \ln(p)$$

$$\text{NCL: } v = N - \lambda \cdot \ln(p)$$

The slope gradient  $\lambda$  is a measure of soil compressibility and is also taken as a compression index.  $N$  and  $\Gamma$  give the position of CSL and NCL on the  $v$ - $\ln p$  plane and, indirectly, the extent of the super-critical and sub-critical zone.

On the other hand, soil shear strength is commonly expressed by the well known Coulomb law in terms

of cohesion “ $c$ ” and the coefficient of internal sliding friction  $\tan \phi$ . Because the tests carried out to analyze sodicity effects on mechanical properties were substantially shear tests, Coulomb law parameters were also measured.

#### The soil

Tests have been carried out with a soil previously treated for sodication at different levels. The treatments were done at the DISTA (Dipartimento di Scienze e Tecnologie Agroambientali, Università di Bologna, Italy) with solutions containing  $\text{ClNa}$  and  $\text{Cl}_2\text{Ca}$  (For more details see [15]). Tests have been focused on two level of sodicity.

The tested soil is a Udertic Ustochrept Clay-silty Loam (USDA) with vermiculite, illite, smectite and caolinite clay minerals, organic matter 15.9 g/kg. The two brackish water treatments produced the following two sodicity traits<sup>1</sup>:

A: SAR 9.85; ESP 5.21;

EC 0.98 dSm<sup>-1</sup>;

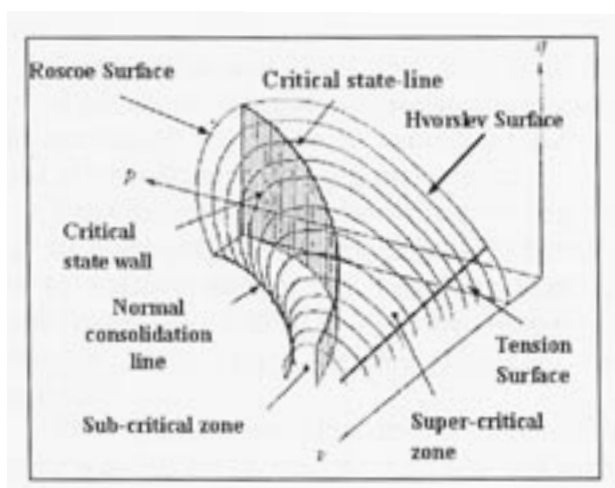
B: SAR 2.86; ESP 1.26;

EC 1.37 dSm<sup>-1</sup>.

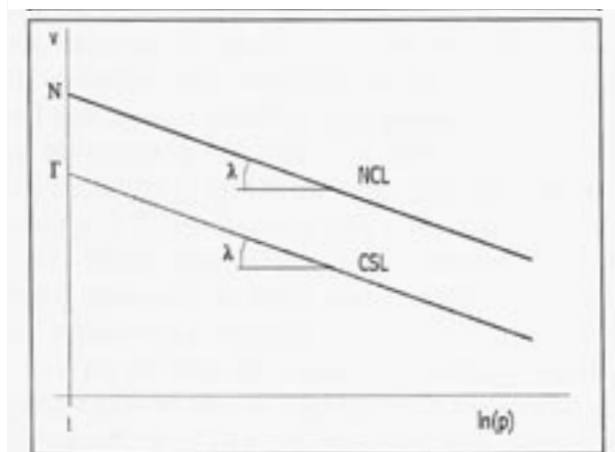
The soil with the two different sodicity levels will be indicated in the following by the symbols A and B.

#### Testing equipment

To determine the soil mechanical parameters a direct shear box apparatus and a measuring procedure similar to that described by Kirby [10] was utilized. It allows the measure of the horizontal shear force and displacement as well as the vertical displacement related to the sample volume change. The measure of volume change during shear permits to discriminate between supercritical and sub-critical behaviour, i.e. to evaluate if the stress-strain path reaches the critical state in a way that result in the loosening or in the compaction of the soil. The normal consolidation line is determined by a one-dimensional compression (oedometer) test, detecting the compression force and the settlement of the top loading platen with respect to the bottom. The position of the critical state line in the  $q=0$  plane is determined interpolating the points which correspond at volume expansion or reduction. The test is quite powerful been apt to assess critical state, virgin line (i.e., the Normal Consolidation Line, indicated as V.L. in the following figures) and Coulomb-Mohr parameters. The shear box cell is cylindrical with a diameter of 63mm and 40mm of height. To detected shear force a load cell of a sensitivity of 2mV/V (550 daN FS). Displacements have been measured by LVDT transducers of a sensitivity of 130 mV/mm (horizontal movement), 780 mV/mm (vertical movement during shear) and 130 mV/mm (vertical movement during compaction). The apparatus is provided with a data logger (GOULD TA11) controlled by a computer.



(a)



(b)

Fig. 1 - Soil states loci in  $p$ - $q$ - $v$  space [4] (a) and plot of critical state and normal consolidation line in  $v$ - $\ln p$  plane (b).

<sup>1</sup> SAR and EC were determined on the extracts of the soil: water 1:5.

### Soil samples preparation and treatments.

The soil previously described (Ozzano A and B) have been sieved and aggregates with dimension between 3.36 and 2mm retained for the tests.

Compression and shear tests have been then carried out on soil samples simply air dried and on soil previously wetted up to saturation and then dried at a moisture of 0.15 g/g (mean value).

The objective of granular not wetted soil tests was to highlight possible mechanical differences due to sodicity without any added treatment (to those made by DISTA). For the purpose of reference these soil samples will be said “granular”.

The residual humidity at the moment of testing was 5% for Ozzano A and 5.6% for Ozzano B. The soil samples were formed pouring a mass of 100g of soil aggregates into the shear box cell. Four samples for each treatment have been used. Each sample was vertically compressed up to a final pressure of 605kPa, then partially discharged and horizontally sheared in a way similar to that used by Kirby [10]. Of the four samples, two were shared at a Stress Ratio of 0.6, one of 0.20 and one of 0.1. Stress Ratio (S.R) is the ratio between the normal pressure at shear and the pre-compaction final pressure, i.e. 605kPa.

With the aim of simulating a natural wetting-drying cycle so that to highlight the dispersion and slaking effect of Na on clay, the two soils have been subjected at a process of saturation and drying as described in the following. Pie samples of 800g (dry weight) of soil was formed using cylindrical sieves (190mm of diameter), with paper filter at the bottom, as containers. The soil pies were formed arranging the soil in thin layers and moistening them with distilled water spray jets to obtain a total humidity of 0.20g/g. Immediately after, the soil pies were compacted at 0.1kPa for 20 minutes and subsequently allowed to equilibrate for 24h sealing the container by plastic film. Soil pie samples were then brought to saturation by submersion putting them into a larger container and filling water slowly. This method was used with the aim of avoiding the desegregation effect due to a fast increase of pores air pressure [19]. Samples were thus left 30 minutes immersed so that dispersion and slaking due to different ESP could have effect. After draining they were dried in oven at 45°C up to a moisture of 0.15 g/g and left to equilibrate for 48h in a sealed container. Eventually, from every soil pie 4 cylindrical samples with a diameter equal to that of the shear box cell were extracted. Two of them were sheared at a stress ratio of 0.60 and two at a S.R. of 0.20; pre-compaction was still 605kPa. For the purpose of reference these soil samples will be said “cemented”.

### 3. Results and discussion.

#### Compression and shear tests of “granular” soils.

The normal consolidation line of the soils Ozzano A and B are reported in fig. 2. They are obtained by

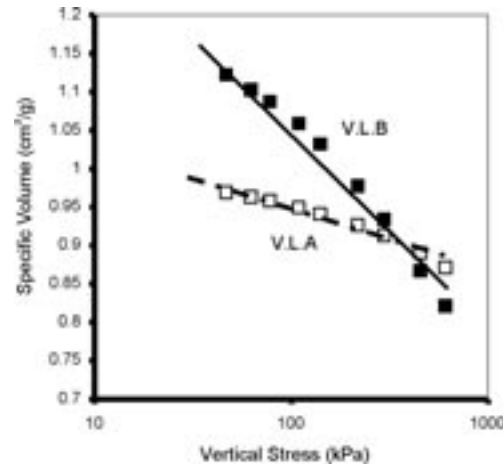


Fig. 2 - Normal consolidation lines (V.L.) of the “granular” soils OzzanoA (ESP 5.21) and OzzanoB (ESP 1.26).

interpolation of four normal consolidation tests and are approximately linear with  $r^2 = 0.96$  either for A than for B. Soil A results less compactable than B and its initial specific volume is lower than B. The A soil aggregates are thus less porous, i.e. more dense, than B. This is due to the higher sodicity of A and at its dispersion effect on clay and subsequent cementation and sealing. The applied normal stress results in a practically similar final compaction for both soils.

Looking at the Coulomb-Mohr's parameters (tab. 1) it may be seen that friction coefficient and cohesion resulted higher for soil A than for soil B (significant difference at  $p < 0.05$ , t-test for paired samples), i.e. soil A is more resistant. Critical state soil mechanics parameters are also reported in tab1. To better understand their meaning, the  $v$ - $\ln p$  diagram of the normal consolidation and critical state lines together with the lines representing the initial and final values of the specific volume (taken horizontal for simplicity) are reported in fig. 3. It may be observed that the distance between the normal consolidation and critical state line is reduced for soil A in comparison with soil B and thus soil A has a smaller sub-critical zone. As a consequence, soil A is less compactable than soil B. From the crossing of the two critical state lines it may be argued that soil A is able to expand at a normal stress higher than soil B. Eventually, to resume the initial porosity, soil B need less shear stress than A (which has a higher cohesion) and its expansion is about threefold that of A (how can be deduced from the total specific volume variation, fig. 3).

	$\text{tg}\phi$	C (kPa)	$\lambda$	G	N
A	0.5464	70.77	-0.0347	1.0714	1.1059
B	0.4901	56.00	-0.1087	1.4056	1.5458

TABLE 1 - Coulomb-Mohr's and Critical state theory parameters for “granular” soil samples Ozzano A (ESP 5.21) and B (ESP 1.26).

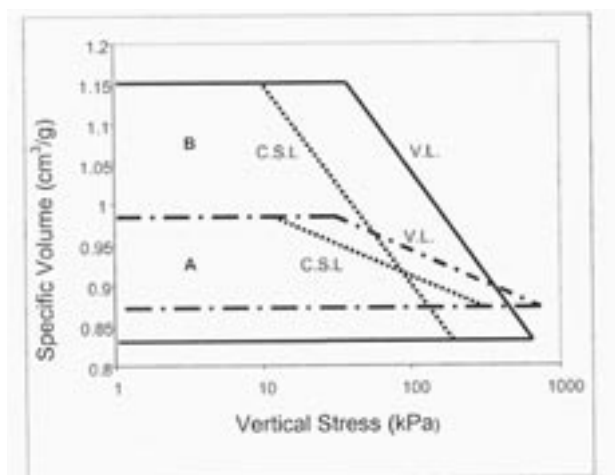


Fig. 3 - Normal consolidation and critical state lines of the “granular” soils OzzanoA (ESP 5.21) and OzzanoB (ESP 1.26). The horizontal lines representing the initial and final specific volume of the tested soil samples are also reported.

#### Compression and shear tests of “Cemented” soils.

The virgin consolidation lines of these soils are reported in fig. 4 (the  $r^2$  is 0.96 for A and 0.97 for B) together with the same lines of the “granular” ones for comparison. It's evident that soil **A** is, also in this case, less compactable than soil **B** due to the higher density and degree of cementation of soil **A**.

The slope of the consolidation line of the “cemented” samples is smaller than that of “granular” ones (the slope gradient difference is significant at  $p < 0.01$  for soil **A**, while for soil **B** it is significant at  $p < 0.05$ ).

Thus both soils for the effect of moistening and drying are less compactable. Moreover, the slope gradient diminution is about twofold greater for soil **A** than for soil **B**. This may be due to the fact that samples of soil **A** reduce their specific volume more than **B** as a consequence of the wetting-drying cycle. In fact, we may see from the graphs that specific volume reduction at pre-compaction is about 33% for soil **A** and 23% for soil **B**.

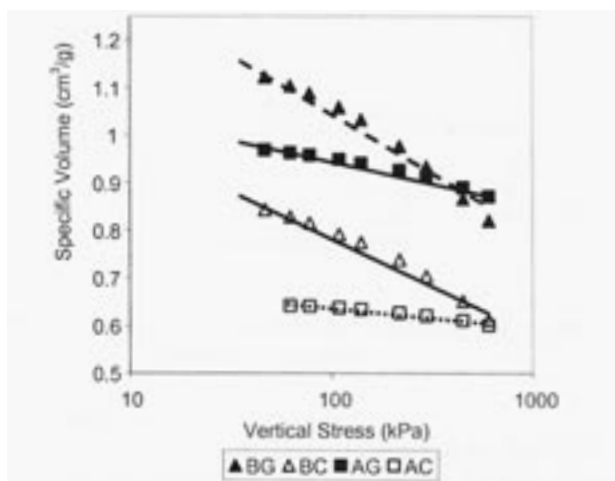


Fig. 4 - Normal consolidation lines of the “cemented” soil samples of OzzanoA (AC) and OzzanoB (BC). The same lines for “granular” soil samples (AG and BG) are also reported for comparison.

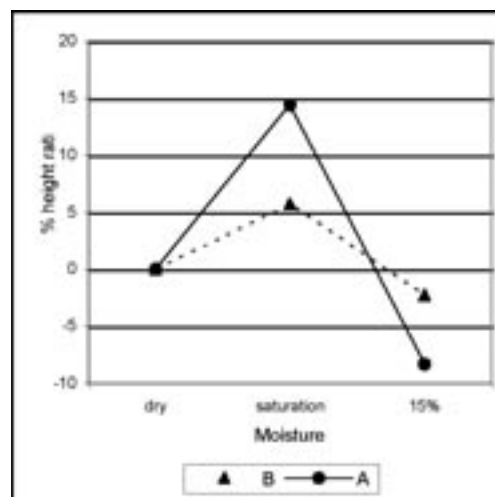


Fig. 5 - Variation of pie samples thickness after saturation and after drying of Ozzano A and B.

The greater specific volume reduction for soil **A** may be due to the higher sodicity and the subsequent higher shrinking effect.

The phenomenon is represented in fig.5 where variation of pie samples thickness after saturation and after drying are shown.

Coulomb-Mohr parameters values as well as those of critical state theory are reported in tab.2.

The wetting-drying treatment results in a more cohesive soil in comparison with the “granular” samples, cohesion that for soil **A** is about twofold and half greater than for **B** (the difference is significant at  $p < 0.1$ ): the wetting-drying cycle amplify the effect of the binomial clay-sodium.

As for critical state theory parameters, the effect of cementation-sealing due to sodium presence is even more evident: the slope of virgin line are less steep and sub-critical area are smaller. A similar result holds for **B** soils. This is well highlighted in the graphs of fig. 6 and 7. From these graphs it may also be noted

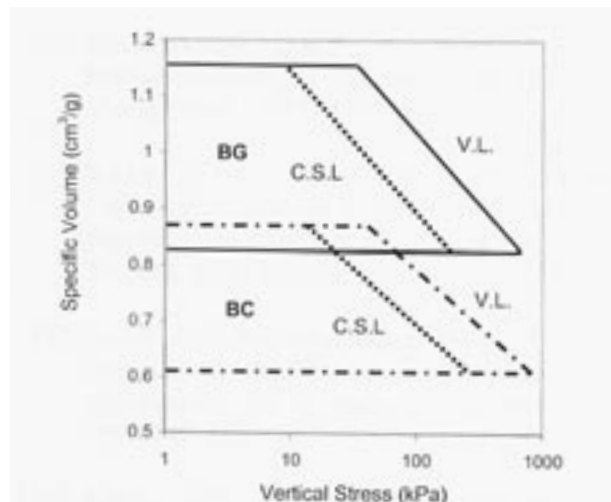


Fig. 6 - Critical state mechanics behaviour diagrams of soil B: ESP 1.26; G=granular, C=cemented.

that pre-consolidation pressure is practically the same for the B soils (31kPa) while for A this pressure has increased for the “cemented” soil samples (AG: 31kPa; AC: 62.15kPa).

	tg $\phi$	C (kPa)	$\lambda$	G	N
<b>A</b>	0.2679	263.43	-0.0176	0.7104	0.7189
<b>B</b>	0.3868	109.79	-0.0835	1.0708	1.1716

TABLE 2 - Coulomb-Mohr's and Critical state theory parameters for “cemented” soil samples Ozzano A (ESP 5.21) and B (ESP 1.26).

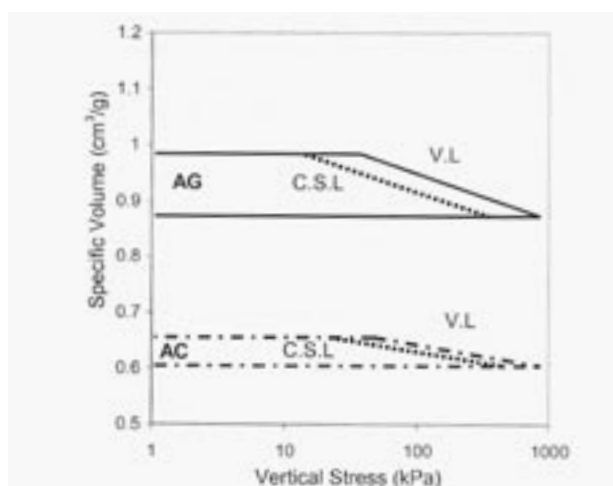


Fig. 7 - Critical state mechanics behaviour diagrams of soil A: ESP 5.21; G=granular, C=cemented.

#### 4. Conclusion

The results show clear differences of the soil mechanical behaviour due to sodicity despite the diversity of the two ESP levels are not so pronounced. The soil samples preparation and treatment methodology used, together with the approach of direct shear box and critical state mechanics, demonstrate to be quite powerful and suitable in assessing the effects of sodicity on soil mechanical properties. Either the tests on the masse of aggregates at air moisture or those on the aggregates subjected to a treatment of wetting up to saturation and draying were effectives. The first is much simpler, the second is nearer to the natural condition of an agricultural soil and amplifies the negative effects of sodicity. In both cases soils with higher ESP have a higher cohesion and therefore they need higher stress states induced by the implements, and likely more energy, to be worked. In the framework of the critical state theory, the higher strength of the more sodic soil results in a lower compaction vulnerability but in a more deviatoric stress state needed to resume its initial macro porosity, i.e. to expand up to the pre-compaction specific volume. This later possibility doesn't mean that the agronomic soil structure functionality could be restored.

#### 5. Bibliography

- [1] BARZEGAR, A.R., MURRAY, R.S., CHURCHMAN, G.J. and RENGASAMY, P., *The Strength of Remoulded Soils as Affected by Exchangeable Cations and Dispersible Clay*, Aust. J. Soil. Res. (1994) **32**, 185-199.
- [2] BARZEGAR, A.R., RENGASAMY, P. and OADES, J.M., *Effects of clay type and rate of wetting on the melowing of compacted soils*, Geoderma (1995) **68**, 39-49.
- [3] CAVAZZA, L., PATRUNO, A. and CIRILLO, E., *Soil Traits and Structure Stability in Artificially Sodicated Soils*, Ital. J. Agron. (2002) **6** (1), 15-25.
- [4] EKO, R.M., *Validation of an extended critical state model using the mechanical behaviour of an agricultural Soil*, Soil & Tillage Research. (2002) **68**, 1-16.
- [5] FABBRI, A., GUARNIERI, A., MARCHESELLI, L., *Effetto dell'irrigazione con acque salino-sodiche su alcune caratteristiche meccaniche del suolo*, Riv. di Ing. Agr. (2003) **1**, 11-16.
- [6] HETTARATCHI, D.R.P., O'CALLAGHAN, J.R., *Mechanical Behaviour of Agricultural Soils*, J. agric. Eng. Res. (1980) **25**, 239-259.
- [7] HETTARATCHI, D.R.P., *A critical state soil mechanics model for agricultural*, Soil Use and Management. (1987) **3** (3), 94-105.
- [8] ILYAS, M., QURESHI, R.H., QADIR, M.A., *Chemical changes in a saline-sodic soil after gypsum application and cropping*, Soil Technology. (1997) **10**, 247-260.
- [9] KIRBY, J.M., *Measurements of the yield surfaces and critical state of some unsaturated agricultural soils*, Journal of Soil Science. (1989) **40**, 167-182.
- [10] KIRBY, J.M., *Strength and deformation of agricultural soil: measurement and practical significance*, Soil Use and Management. (1991) **7** (4), 223-229.
- [11] KIRBY, J.M., *Simulating soil deformation using a critical-state model: I. Laboratory tests*, European J. of Soil Science. (1994) **45**, 239-248.
- [12] KIRBY, J.M., O'SULLIVAN, M.F., *Critical state soil mechanics analysis of the constant cell volume triaxial test*, European J. of Soil Science. (1997) **48**, 71-78.
- [13] LEESON, J.J., CAMPBELL, D.J., *The variation of soil critical state parameters with water content and its relevance to the compaction of two agricultural soils*, J. of Soil Science. (1983) **34**, 33-44.
- [14] MACARI, E.J., HOYOS, L.R., ARDUINO, P., *Constitutive modeling of unsaturated soil behaviour under axisymmetric stress states using a stress/suction-controlled cubical test cell*, Int. J. of Plasticity. (2003) **19**, 1481-1515.
- [15] PATRUNO, A., CAVAZZA, L., CIRILLO, E., *Experiments on Soil Sodication*, Ital. J. Agron. (2002) **6** (1), 3-13.
- [16] QUIRK, J.P., MURRAY, R.S., *Towards a Model for Soil Structural Behaviour*, Aust. J. Soil Res. (1991) **29**, 829-867.
- [17] RAHIMI, H., PAZIRA, E., TAJIK, F., *Effect of soil organic matter, electrical conductivity and sodium adsorption ratio on tensile strength of aggregates*, Soil & Tillage Research. (2000) **54**, 145-153.
- [18] RAJARAM, G., ERBACH, D.C., *Effect of wetting and drying on soil physical properties*, J. of Terramechanics (1999) **36**, 39-49.
- [19] RENGASAMY, P., OLSSON, K.A., *Sodicity and Soil Structure*, Aust. J. Soil Res. (1991) **29**, 935-952.

- [20]. SPUGNOLI P., SOVERINI E., PALANCAR T. (2002). *Effects of Irrigation with brackish water on soil trafficability and workability*. In Pagliai M., Jones R. Sustainable Land Management – Environmental Protection A Soil Physical Approach. (vol. 35, pp. 267-278). ISBN: 3-923381-48-4. Special issue of Advances in GeoEcology. Reiskirchen: Catena Verlag (Germany).
- [21]. TABOADA, M.A., LAVADO, R.S., *Interactive effects of exchangeable sodium and water content on soil modulus of rupture*, Soil Technology. (1996) **8**, 345-349.
- [22]. UTOMO, W.H., DEXTER, A.R., *Soil Friability*, J. of Soil Science. (1981) **32**, 203-213.
- [23]. ZHANG, B., ZHAO, Q.G., HORN, R., BAUMGARTL, T., *Shear strength of surface soil as affected by soil bulk density and soil water content*, Soil & Tillage Research. (2001) **59**, 97-106.

#### SUMMARY

#### MECHANICAL PROPERTIES OF A SODICATED SOIL

The paper reports the results of a set of laboratory tests aimed to analyze the changes in mechanical behaviour of a soil at two different levels of sodicity

(ESP 1.26 and ESP 5.21), simulating the effects of using brackish water.

To relate the volumetric change of soil in response to external loads, the approach followed has been that of the critical state soil mechanics. To this purpose, compression and direct shear tests, together with the measure of samples height variation during shear, have been carried out. Coulomb soil strength parameters were also measured. The sodicated soil has been sieved and only the aggregates with dimension between 3.36 and 2mm retained for the tests. Two kind of soil samples were used: with aggregates simply at air moisture and with a bed of aggregates previously wetted up to saturation and then dried at a moisture of 0.15g/g. Both methods were effective, the first being simpler the second amplifying the negative effects of sodicity. In both cases soils with higher ESP had a higher cohesion and a lower compressibility. The higher strength of the more sodic soil results in a lower compaction vulnerability but in a more deviatoric stress state needed to resume its initial macro porosity, i.e. to expand up to the pre-compaction specific volume.

#### Keywords:

Soil mechanics, sodicated soil, Critical State theory.