Influence of Sodicity and Salinity on the Mechanical Properties of two Italian Soils

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ABSTRACT

Soil salinisation has been identified as a major process in land degradation. Sodic soils become less permeable to water and air, more prone to erosion, and require more energy for tillage. To assess the influence of irrigation with brackish water on soil mechanical characteristics, field and laboratory tests were performed on two different Italian soils. One soil was irrigated with saline water directly in the field, while the other was treated in the laboratory with sodic solutions at different concentrations.

The results have shown that different soils may have a very different response to the treatment with brackish water. The soil sensitive to the saline action greatly reduced its plastic limit and consequently its workability. This is also shown by the significant increase in shear resistance. In addition, the slope of the line used for liquid limit (LL) determination, expressing the sensitivity of the soil to the moisture content, can effectively be used as an index of sensitivity to sodic soils.

keywords:

soil mechanics, sodicity, salinity, Atterberg limits, direct shear test

1. Introduction

1.1. *General considerations and problem description*

Soil salinisation has been identified as a major process of land degradation. It has been estimated from the available data that salinisation is reducing the world's irrigated area by 1-2% every year, hitting hardest in arid and semi-arid regions (Xiao Gang *et al.*, 2002). Based on a soil map of the world, made by the Food and Agriculture Organisation (FAO) and United Nations Educational Scientific and Cultural Organisation (UNESCO), the total area of saline soils is 397 million ha and that of sodic soils is 434 million ha. Of the current 230 million ha of irrigated land, 45 million ha are salt-affected soils (about 19%), and of the almost 1500 million ha of dryland agriculture, 32 million are salt-affected soils (2%) to a greater or lesser degree human-induced (Oldeman, 1991; Brandt & Thornes, 1996; Middleton & Thomas, 1997; FAO, 2000 & 2002).

Saline and alkali (or sodic) soils are characterised by excess salts that modify their chemical and physical properties. If carefully managed, saline soils can maintain a suitable structure and permeability to water and air. Sodic soils, on the contrary, are affected by clay dispersion and structural instability. They become less permeable to water and air, with scarce workability. Degradation of the soil structure also increases soil erodibility.

In terms of field operations, increased energy requirements due to reduced trafficability and workability, and increasing compaction damage are the most important consequences of soil salinisation and sodicisation (Spugnoli *et al.*, 2002).

1.2. *Aims of the research*

In order to assess the influence of salinity and sodicity on mechanical characteristics of two Italian soils, the Atterberg limits were measured, as these can be used to define mobility and

tillage limits (Fabbri *et al.*, 1997; Crescimanno & Provenzano, 2000; Müller *et al.*, 1990; Freitag, 1987; Mckyes, 1985).

In addition, Direct Shear (DS) tests were also performed (Fabbri *et al.*, 2001; Dexter & Chan, 1991), because shear parameters are correlated with the energy spent on mobility and tillage (Kogure *et al.*, 1982; Bekker, 1960; Wong, 1989; Dexter, 1975).

2. Materials and methods

The DS tests and Atterberg limits measurement regarded two different soils from two areas of Italy: Matera (Metaponto region) and Ozzano (Bologna region). Table 1 summarises the principal soils characteristics.

The Matera soil had been subjected, before sampling, to a normal irrigation cycle with brackish water for some years. Six random samples were taken from this area, the chemical characteristics of which are reported in Table 2. The Ozzano soil samples were obtained after laboratory treatement with different NaCl and $CaCl_2$ solutions, to obtain four different soils characterised by the exchangeable sodium percentage (ESP) and electrical conductivity (EC) values reported in Table 2.

As regards the Atterberg limits, the British Standard Institution (BSI 1377, 1975) was followed, using a dynamic cone penetrometer for liquid limit (LL) determination, while for plastic limit (PL) determination, the minimum moisture content needed to permit the plastic modelling of small soil cylinders (~3 mm diameter) without cracking was measured. Before these measurements the soil was sieved at 0.45 mm and humidified at a value close to 15% of moisture (dry basis), then rested for 24 hours. Eight replicates were done of each PL measurement, and six for LL. In addition to the LL measurement, the slope of the regression line was evaluated, as this could be an index of the soil consistency sensitivity to water (*Fig. 1*).

A DS machine was used for soil deformability in the plastic field, with a shear box measuring 60 mm by 60 mm and three consolidation cells. Each soil sample was sieved at 2 mm, placed in a flat container, and humidified by applying water from the top. After humidification, the soil samples were rested for 24 hours to achieve a more uniform moisture content. Great care was taken to control the moisture content so as to maintain the soil moisture close to PL, *i.e.*, close to optimal working conditions.

The soil was then compacted inside drained consolidation cells loaded by a vertical force of 500 N (corresponding to a pressure of 140 kPa) according to the American Society for Testing and Materials (ASTM) drained consolidation method (ASTM D3080, 2003; ASTM D2435, 2003). The six samples for each thesis were rested for 72 hours.

The DS machine was equipped with two displacement transducers: one for horizontal displacements of the shear box (25 mm max, accuracy 0.01 mm) to evaluate shear deformation, and another vertical (10 mm max, accuracy 0.001 mm) to check the volume variation of the cell during the test according to the ASTM standard. The shear force was measured by a loading cell (5 kN maximum load, accuracy 0.1% full scale).

The DS machine was configured to perform 4 complete loading-unloading cycles with an imposed displacement of 9 mm at a speed of 0.117 mm/s. The force-displacement values were read by a digital acquisition card (National Instruments 333 kSample/s, 16 input lines, 16 bit resolution) and a LabView software interface. On the force-deformation plots (see *Fig. 2* as an example) the mean area was calculated on three closed cycles (A_m) and the difference between the maximum and minimum force value (ΔF) was evaluated.

At the end of each test, the soil sample was removed from the shearbox for moisture content (m) and bulk density (γ) measurement. The complete laboratory tests required about one year.

3. Results

3.1. Atterberg limits

The Atterberg limits measured on the Matera soil were processed, looking for correlation between changes in mechanical parameters and treatment with brackish water.

The analysis of variance (ANOVA) test showed significant differences between the PL values, due to changes exchangeable sodium percentage (ESP) and electrical conductivity (EC), even if the linear correlation test shows no influence between Atterberg limits and treatments (Table 3 & 4). These results have to be interpreted in relation to the high concentrations of non-swelling minerals (almost kaolinite) in the Matera soil, as they make it difficult for water and sodium to enter the crystal lattice. Moreover, as expected, and supporting the validity of the measurement, the values of ESP and EC were found to be strictly correlated (Table 5).

As regards the lab tests on Ozzano soil, the LL was found influenced by the pH of the sodic solution and a positive interaction between pH and ESP on LL was also found. The slope variable behaves in the same way, even if the ESP influence is stronger than with LL. While there is a correlation for PL with all the controlled variables, the interaction effects are less evident (Table 4).

In all cases, the correlation is negative. This is in agreement with the fact that increasing the sodicity for the Ozzano soil leads to increased soil consistency and a consequent increased resistance to penetration of the dynamic cone device for LL measurement (Baver, 1948; Fabbri *et al.*, 2003).

Also for Ozzano soil, it should be noted that ESP, EC and pH values are almost proportional (Table 5).

3.2. Direct shear tests

The data in Table 6 show that, as expected, bulk density and moisture content strongly affect all the mechanical parameters. This justifies the care spent in controlling these parameters with adequate precision to avoid masking of effects due to variation of salinity. In particular, bulk density was almost the same for all the laboratory samples: around 1363.8 kg/m^3 with a standard deviation of 39.2 kg/m^3.

The mechanical parameters of the Ozzano soil were very sensitive to salinity variations, while the Matera soil was not. As regards the former, the influence of the treatment with brackish water is significant on the variables A_m and ΔF. This arose both from linear regression and nonparametric correlation, which can characterise even a nonlinear relationship between the variables (Table 6). The high influence of PL on shear parameters is also notable, but not of LL. This is probably due to the physical similarity in plastic deformation action in the DS test and in forming the small cylinders for PL measurement.

4. Conclusions

The two tested soils reacted to the brackish water treatment in a very different way relative to their mineral composition. The Ozzano soil was very sensitive while the Matera was not. For the Ozzano soil, the parameter Slope was found to be better at differentiating the theses than the Atterberg limits.

The correlation of Atterberg limits with soil concentration is negative, *i.e.*, the sodium can reduce the plasticity field, so the soil requires more energy for tillage.

As regards the direct shear tests, it was verified that great care is required in controlling the values of bulk density and moisture content, as their variations can easily mask any physical modifications induced by the brackish water treatment. Finally, the observed variations of

Plastic Limit and shear parameters were similar, according to the fact that these two tests both involve plastic deformations of the soil.

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CAPTIONS, FIGURES AND TABLES

Fig. 1. Regression line for liquid limit measurement; the slope of the line represents sensitivity of the soil to water

Fig. 2. Force-displacement plot in direct shear test

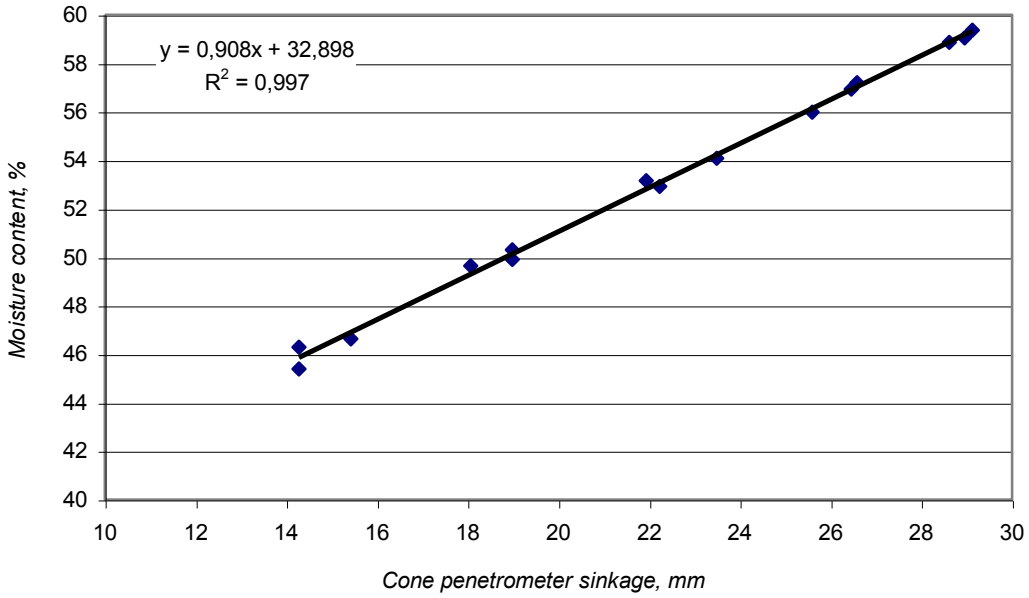

Fig. 1. Regression line for liquid limit measurement; R^2, coefficient of determination

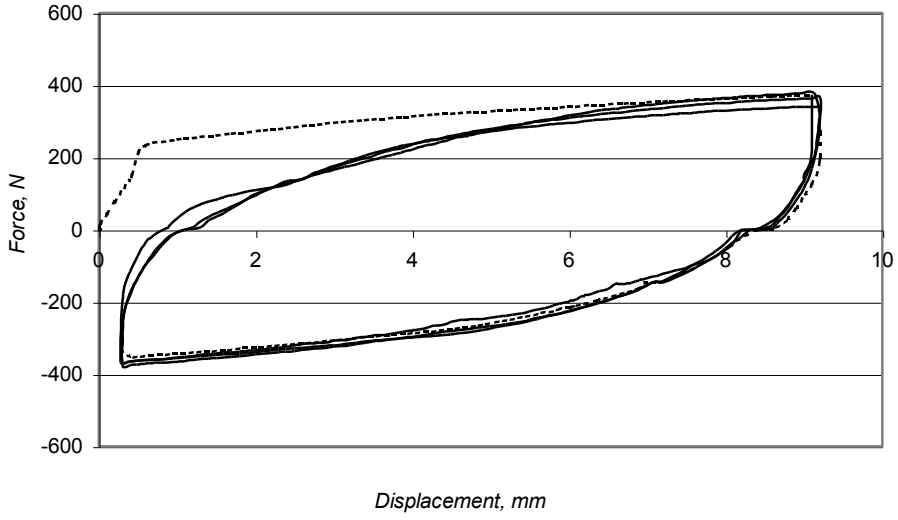

Fig. 2. Force-displacement plot in direct shear test

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1 **Table 1**

2 **Mineralogy composition and particle-size of Ozzano and Matera soils**

Soil	*Mineralogy composition, %*				*Soil particle size distribution, %*		
	Illite	*Chlorite*	*Kaolinite*	*Swelling*	*2-0.05 mm*	*0.05-0.002 mm*	*<0.002 mm*
Matera	12	26	50	12	2.60-5.65	46.32- 52.84	41.51-50.92
Ozzano	53	10	12	25	13.69	47.68	36.63

1 **Table 2**

2 **Chemical analysis of Ozzano and Matera soils. For each sample the values of electrical**

3 **conductivity, exchangeable sodium percentage and pH of a 1:5 water-soil solution are**

4 **reported. The not treated samples were respectively the 1 and 7**

Soil	*Sample*	*electrical conductivity, %*	*exchangeable sodium percentage, dS m^{-1}*	*pH*
Matera	1	0.20	0.35	7.28
	2	0.76	0.49	7.46
	3	2.83	1.07	7.47
	4	3.11	0.72	7.38
	5	9.17	1.23	7.33
	6	9.27	0.72	7.65
Ozzano	7	0.60	0.14	7.89
	8	5.21	0.98	8.09
	9	14.33	1.12	8.3
	10	25.20	1.30	9.11

Table 3

Analysis of variance (ANOVA) test for variable plastic limit (PL) with respect to exchangeable sodium percentage (ESP), electrical conductivity (EC) and pH for Matera soil

Variables	*Sums of squares error (SS)*	*Mean sums of squares error (MS)*	*Fischer variance ratio (F)*	*Significance (p)*	*Degree of freedom*	*F critical for 95%*
ESP	6.05	6.05	5.02	0.03	1	4.06
EC	8.16	8.16	6.78	0.01	1	4.06
pH	0.03	0.03	0.02	0.88	1	4.06
error	53.03	1.20	-	-	44	-

1 **Table 4**

2 **Correlation between liquid limit (LL), plastic limit (PL), slope, exchangeable sodium**

3 **percentage (ESP), electrical conductivity (EC) and pH for Matera and Ozzano soil**

Correlated variables	*Matera*		*Ozzano*	
	Linear regression coefficient	*Significance (p)*	*Linear regression coefficient*	*Significance (p)*
LL & ESP	-0.14	< 0.01	-0.40	0.20
LL & EC	-0.22	0.38	-0.02	0.94
LL & pH	-0.37	0.13	-0.58	0.05
LL & ESxpH	-	-	-0.60	0.04
Slope & ESP	0.05	0.84	-0.65	0.02
Slope & EC	0.16	0.53	-0.23	0.48
Slope & pH	-0.21	0.39	-0.76	< 0.01
Slope & ESxpH	-	-	-0.79	< 0.01
PL & ESP	0.16	0.27	-0.41	< 0.01
PL & EC	0.19	0.19	-0.38	0.03
PL & pH	0.19	0.19	-0.37	0.04
PL & ESxpH	-	-	-0.37	0.04

1 **Table 5**

2 **Correlation between exchangeable sodium percentage (ESP), electrical conductivity**

3 **(EC) and pH for Matera and Ozzano soil**

Correlated variables	*Matera*		*Ozzano*	
	Linear regression coefficient	*Significance (p)*	*Linear regression coefficient*	*Significance (p)*
ESP & EC	0.64	< 0.01	0.83	< 0.01
ESP & pH	0.42	< 0.01	0.97	< 0.01
EC & pH	0.05	0.66	0.75	< 0.01

Table 6

Parametric and non-parametric matrices for the Ozzano soil; LL, liquid limit; PL, plastic limit; ESP, exchangeable sodium percentage; EC, electrical conductivity; A_m, mean area; ΔF, difference between the maximum and the minimum force value; m, moisture content (dry basis); γ, bulk density

Correlated variables	*Linear correlation*		*Spearman Rank Order Correlations*		
	Linear regression coefficient	*Significance (p)*	*Spearman*	*Student t (t)*	*Significance (p)*
A_m & ESP	0.60	0.01	0.72	3.83	< 0.01
A_m & EC	0.71	< 0.01	0.72	3.83	< 0.01
A_m & pH	0.53	0.03	0.72	3.83	< 0.01
A_m & PL	-0.66	< 0.01	-0.72	-3.83	< 0.01
A_m & LL	0.01	0.96	0.04	0.14	0.89
A_m & Slope	-0.17	0.52	-0.08	-0.32	0.75
A_m & γ	-0.41	0.11	-0.48	-2.06	0.06
A_m & m	-0.85	< 0.01	-0.74	-4.13	< 0.01
ΔF & ESP	0.50	0.05	0.49	2.08	0.06
ΔF & EC	0.56	0.02	0.49	2.08	0.06
ΔF & pH	0.43	0.09	0.49	2.08	0.06
ΔF & PL	-0.55	0.03	-0.49	-2.08	0.06
ΔF & LL	0.02	0.94	0.24	0.94	0.36
ΔF & Slope	-0.15	0.57	0.07	0.27	0.79
ΔF & γ	-0.40	0.12	-0.33	-1.31	0.21
ΔF & m	-0.94	< 0.01	-0.85	-6.04	< 0.01