



Effects of iron and aluminum oxides and clay content on penetration resistance of five Greek soils

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Abstract

The effect of amorphous and crystalline iron (Fe) and aluminum (Al) oxides and oxy-hydroxides as well as clay on soil penetration resistance of five Greek soils, as a function of soil water suction was studied for the whole range of soil moisture. The soils tested were of loamy texture and were collected from cultivated and non-cultivated areas of north and central Greece (Macedonia and Thessaly). The study aimed at understanding the role of the above mentioned soil components on penetration resistance.

The findings showed that the increase of iron and aluminum oxides and oxy-hydroxides content resulted in an increase of soil penetration resistance and the relationships between them were significant. Crystalline iron forms found to have a more profound effect on penetration resistance as compared to amorphous iron forms. Finally, positive and significant relationships were also found between penetration resistance and clay content. However, it is not entirely clear which of the two soil components plays the most important role in penetration resistance changes in soils.

Keywords: penetration resistance, soil water suction, Fe and Al oxides and oxy-hydroxides, clay

Article Info

Received : 14.05.2013

Accepted : 08.09.2013

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Introduction

Penetration resistance (PR) is a measure of soil strength and of mechanical obstruction the root system faces during plant growth. The value of this property varies widely between soils as well as within the same soil, when certain conditions are changing (i.e. soil moisture or soil water suction) or where cultivation practices are not appropriate, such as frequent movement and operation of heavy farm vehicles and machinery under not appropriate soil conditions.

Increased PR may also be the result of natural processes, such as clay flocculation, clay movement, repeated cycles of drying and wetting that cause soil shrinking and swelling, respectively, as well as pressure due to the development of the plants' root system. Also the particle size composition, if the individual soil particles are present in specific and definite proportions, could be a cause of increased PR. Finally, the increased PR may be due to endogenous factors, such as the presence of various forms of Fe and Al oxides and oxy-hydroxides.

In the relevant literature, the study of the role of Fe and Al oxides and oxy-hydroxides has mainly focused on the formation of compacted soil horizons (hardpans, duripans, hardsetting) which, according to Soil Taxonomy System (Soil Survey Staff, 1999), are recognized as genetic soil horizons (Witty and Knox, 1989). According to Smith and Callahan (1987), Fe oxides and oxy-hydroxides are not considered as possible cohesive or coagulating agents of soil particles, though they play a significant role in cementing some soils

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ISSN: 2147-4249

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(Schwertmann and Taylor, 1977). Ajmone Marsan and Torrent (1989) argue that Fe oxides and oxy-hydroxides are not directly involved in the aggregation of soil particles but only indirectly, because they contribute towards holding the particles to each other with other mechanisms. According to the same researchers, the surface of Fe oxides is more active than that of clay minerals. Consequently, Fe oxides and oxy-hydroxides have the necessary surface area for the initial H_4SiO_4 absorption which is present in the soil solution. The absorbed H_4SiO_4 acts as a condensation agent forming nucleus which absorbs additional quantities of H_4SiO_4 . When the soil dries, the absorbed H_4SiO_4 molecules become dehydrated and SiO_2 is formed (Chadwick et al., 1987). According to Steele et al. (1969), amorphous (non crystalline) Fe and Al oxides and oxy-hydroxides may contribute to the fragile nature of some soil horizons. Harlan et al. (1977) argue that the higher clay content in soil horizons containing Fe and/or Al oxides and oxy-hydroxides is the reason for the increased PR, while the oxides and oxy-hydroxides themselves do not affect the soil particle aggregation. Lindbo and Veneman (1993) state that Fe and Al removal using appropriate extracting agents was related with PR decrease. Also, simultaneous clay removal resulted in furthermore PR decrease.

When PR exceeds a limit (≈ 3 MPa) the plants' root growth is slowed down or stops (Mullins et al., 1990; Panayiotopoulos et al., 1994). Similar effects on the root system are also observed under conditions of increased soil water suction. PR also largely depends on soil moisture and soil water suction (Brady and Weil, 2007), therefore the knowledge of soil moisture or soil water suction at which PR measurements must be taken to ascertain whether this property is a limiting factor for roots growth, is of particular interest. Young (1987) and Ley (1988) measured the PR of undisturbed soil samples, previously equilibrated to different soil water suction values and found that PR values equal to 3 MPa were measured in those samples that had previously been equilibrated at 0.1 - 0.2 MPa soil water suction.

Although Fe and Al oxides and oxy-hydroxides contribute to soil particles and structural units bonding and to the formation of more compacted soil horizons, their effect on PR has not been adequately studied. The aim of this work was to study the effect of Fe and Al oxides and hydroxides as well as clay on PR of five Greek soils that were equilibrated to different soil water suction values.

Material and Methods

Soil samples were collected from three areas of Northern Greece (Macedonia), N. Halkidona, Veria and Souroti, and one area of Central Greece (Thessaly), Larisa (Figure 1). The sampling depths in each soil profile are presented in Table 1. From each soil profile and depth, both undisturbed and disturbed soil samples were collected.



Figure 1. Study areas

Table 1. Basic physical and chemical properties of the soils

depth (cm)	sand (%)	silt (%)	clay (%)	γ_d (g cm ⁻³)	porosity (%)	pH (paste saturation)	O.M (%)
1A profile							
0-40	34.75	44.40	20.85	1.33	49.68	7.7	2.52
40-80	23.56	54.45	21.99	1.20	54.84	8.1	1.02
80-95	22.07	53.06	24.87	1.50	43.27	7.8	0.29
>95	23.85	49.51	26.64	1.44	45.66	8.1	0.22
1B profile							
0-40	36.03	43.75	20.22	1.33	49.94	7.8	1.88
40-80	18.98	56.32	24.70	1.24	53.33	8.1	1.74
80-95	23.47	52.97	23.56	1.29	51.32	8.7	1.17
>95	17.08	54.31	28.61	1.44	45.85	8.7	1.09
2A profile							
0-20	33.03	55.41	11.56	1.34	49.56	7.6	2.41
>20	25.12	58.58	16.30	1.20	54.59	7.9	0.57
2B profile							
0-12	53.55	36.42	10.03	1.23	53.59	8.0	1.19
>12	33.92	54.37	11.71	1.28	51.57	8.3	0.52
3A profile							
0-10	47.83	21.80	30.37	1.40	47.17	7.9	1.84
3B profile							
0-10	65.21	19.12	15.67	1.39	47.67	7.2	1.46
4A profile							
0-30	46.38	33.78	19.84	1.50	43.40	7.6	2.78
>30	46.93	34.01	19.06	1.60	39.69	7.8	1.55
4B profile							
0-30	35.50	42.52	21.98	1.29	51.32	7.7	2.76
>30	33.98	44.47	21.55	1.44	45.41	7.8	2.28
4C profile							
0-30	41.70	39.51	18.79	1.51	43.14	6.8	0.72
>30	43.09	39.66	17.25	1.67	37.23	6.3	0.53
4D profile							
0-30	60.56	28.67	10.77	1.24	53.21	7.5	0.93
>30	61.35	27.82	10.83	1.42	46.40	7.2	0.69

More specifically, in N. Halkidona area soil samples were collected from two sites (1A, 1B) of a poplar tree cultivation located in the state forest nursery. In Veria area, the sites of soil sampling (2A, 2B) were selected from uncultivated land. In Souroti area, two soil samples (3A, 3B) were also collected from uncultivated land. In Larisa area, the 4A and 4B sites were located in cotton fields, while 4C and 4D sites were located in almond trees fields. The selection of study areas was based on evidence of possible soil compaction problems.

The undisturbed soil samples were collected by means of metallic cylinders of 5.7 cm diameter and 4.0 cm height. These samples were used for the determination of PR and bulk density (γ_d) of the soils. From the base of the undisturbed samples, a thin (3-4 mm) soil layer was removed and the space formed was filled with gypsum and water at a 6:5 v/v ratio, respectively. This was necessary for supporting the soil samples in the cylinder, as well as for securing a hydraulic contact between the soil samples and the ceramic disc on which the soils were equilibrated prior to the determination of PR.

The undisturbed soil samples were saturated with a 0.005M CaSO₄ solution to avoid clay dispersion. The saturation took place under 2-3 kPa suction. After saturation, the samples were placed in a pressure membrane apparatus where the equilibration took place under 1, 10, 100, 1000 and 10⁵ kPa suction.

The conical edge of the penetrometer used, had an angle of 60°, a base diameter equal to 3 mm and a penetration velocity of 1,52 mm min⁻¹. PR was calculated as the resistance the conical edge faces in order to penetrate a depth of 10 mm from the surface of the sample via the cross-section of the conical edge base (Bengough and Mullins, 1990). For the PR determination, three undisturbed soil samples were used for each soil water suction value and two measurements were conducted on each sample.

Bulk density, γ_d , was also determined in undisturbed soil samples in three replications, according to the equation $\gamma_d = M / V$, where M is the mass and V is the dried volume at 105 °C (Blake and Hartge, 1986). Total porosity, n, was calculated by means of the relation $n = 1 - (\gamma_d / \gamma_s)$, where γ_s is the density of the soil particles (2.65 g cm⁻³).

The disturbed soil samples, after being air dried in the laboratory, were ground and sieved to pass a sieve of 2 mm openings diameter. In the < 2 mm soil particles, the following were determined; i) particle size distribution by means of pipette method (Gee and Bauder, 1986), ii) organic carbon by wet oxidation method (Nelson and Sommers, 1982), iii) pH in the saturated paste (McLean, 1982). In addition, amorphous Fe and Al oxides and oxy-hydroxides (Fe_o, Al_o) were determined after being extracted by 0.2 M NH₄ oxalate at pH 3, poorly crystalline Fe and Al (Fe_s, Al_s) were determined after being extracted by 0.5M NaOH and total "free" Fe oxides and oxy-hydroxides (Fe_d) were determined using the citrate - bicarbonate - dithionite Na (CBD) method (Jackson et al., 1986). Fe and Al extracted by the above mentioned procedures were determined by atomic absorption spectroscopy (AAS) in two replications.

The statistical data analysis was done by means of SPSS® and Microsoft Excel®. The comparisons were made using ANOVA based on the LSD (Least Significant Difference) test.

Results and Discussion

In Table 1 some basic physical and chemical properties of the soils studied are presented. The soils of Halkidona area as well as those of Veria are characterized as Entisols. On the other hand the soils of Souroti area and those of 4A and 4B profiles of Larisa are characterized as Inceptisols. Specifically, the soils of Larisa are Ochrepts Xerochrepts. The soils of the 4C and 4D profiles of Larisa are characterized as Alfisols, namely Xeralfs Haploxeralfs. All soils are categorized as loams (L); organic matter content varies between 0.22 and 2.78%; bulk density ranges between 1.20 and 1.67 g cm⁻³ and all soils are alkaline except the soils of profile 4C which are neutral to slightly acidic.

Fe and Al oxides and oxy-hydroxides and Fe_o/Fe_d ratio

In Table 2, the concentrations of Fe extracted by different solutions are presented. From the presented data it is apparent that: a) in all soils except those of Halkidona region, there is no significant (P<0.05) difference in Fe concentrations with depth, b) the studied soils differ in their concentrations in extracted forms of Fe and c) in Halkidona soils, the extracted Fe forms show statistically significant differences at different depths.

One notable aspect is the ratio of Fe extracted by ammonium oxalate (Fe_o) to Fe extracted by citrate-bicarbonate-dithionite sodium (Fe_d). This ratio (Fe_o/Fe_d), called active iron, expresses the fraction of non-crystalline (amorphous) to the total concentration of Fe oxides and oxy-hydroxides (both crystalline and amorphous) and can range from about 0 to 1. In general, greater values of this ratio are observed in surface soil horizons due to the fact that the conversion of amorphous Fe compounds in crystalline ones is slowed down by the increased presence of organic matter (Schwertmann and Cornell, 1991). The same researchers state that the Fe_o/Fe_d ratio is significantly changed in deeper soil horizons, and more specifically in wet soils of temperate regions taking values between 0.2 – 0.4. Values < 0.1 are predominant in older and mature soils (Tsaousidou et al., 2008).

It is evident that the Fe_o/Fe_d ratio shows a decrease trend with depth, which is in accordance with the findings of Schwertmann and Cornell (1991). This is justified by the slow crystallization of the amorphous Fe oxides caused by the organic matter, which is increased in the surface layers.

The concentrations of Al extracted by 0.2 M ammonium oxalate (Al_o) and by 0.5 M boiling NaOH (Al_s) are also presented in Table 2. There is no significant (P<0,05) change of Al_o concentrations with depth, the studied soils differ in their concentrations of extracted Al and in almost half the soils studied, the extracted Al_s shows statistically significant differences at different depths.

Table 2. Extracted Iron and Aluminum concentrations and Fe_o/Fe_d ratio values.

area	soil profile	depth (cm)	Fe _o ⁽¹⁾ (μg g ⁻¹)	Fe _d ⁽²⁾ (μg g ⁻¹)	Fe _s ⁽³⁾ (μg g ⁻¹)	Fe _o /Fe _d	Al _o ⁽¹⁾ (μg g ⁻¹)	Al _s ⁽³⁾ (μg g ⁻¹)
Halkidona	1A	0-40	1646 ^{a*}	7322 ^a	526 ^a	0.22	462 ^a	1837 ^a
		40-80	1396 ^{ab}	7491 ^a	542 ^a	0.19	431 ^a	1880 ^a
		80-95	1132 ^b	8999 ^b	230 ^b	0.13	334 ^b	1994 ^a
		>95	1460 ^{ab}	11031 ^c	237 ^b	0.13	493 ^a	2416 ^b
	1B	0-40	1469 ^a	7518 ^a	802 ^a	0.20	334 ^a	2226 ^a
		40-80	1608 ^b	8014 ^b	457 ^{ab}	0.20	410 ^{ab}	2286 ^a
		80-95	1208 ^c	6575 ^c	546 ^{ab}	0.19	460 ^b	1551 ^b
		>95	1167 ^c	9665 ^d	437 ^b	0.12	464 ^b	1916 ^c
Veria	2A	0-20	1047 ^a	5283 ^a	444 ^a	0.20	373 ^a	1314 ^a
		>20	1445 ^a	6202 ^b	434 ^a	0.23	444 ^a	1086 ^b
	2B	0-12	1485 ^a	4702 ^a	***	0.32	334 ^a	842 ^a
		>12	1477 ^a	5067 ^a	***	0.29	304 ^a	946 ^a
Souroti**	3A	0-10	455 ^a	6610 ^a	273 ^a	0.07	490 ^a	2830 ^a
	3B	0-10	376 ^a	4100 ^b	269 ^a	0.09	497 ^a	1143 ^b
Larisa	4A	0-30	1331 ^a	4607 ^a	477 ^a	0.29	493 ^a	1035 ^a
		>30	1336 ^a	4934 ^b	443 ^a	0.27	544 ^a	1049 ^a
	4B	0-30	394 ^a	4390 ^a	310 ^a	0.09	419 ^a	1389 ^a
		>30	255 ^a	4534 ^a	343 ^a	0.06	335 ^a	1328 ^b
	4C	0-30	615 ^a	4703 ^a	437 ^a	0.13	264 ^a	1778 ^a
		>30	549 ^a	4601 ^a	405 ^a	0.12	237 ^a	1666 ^a
	4D	0-30	384 ^a	3524 ^a	284 ^a	0.11	211 ^a	1178 ^a
		>30	283 ^a	3349 ^a	282 ^a	0.08	171 ^a	1211 ^a

* Values accompanied by the same letter do not differ significantly (P<0.05).

The comparison was done perpendicularly between the depths and for each profile separately.

** The comparison was done between 3A and 3B surface soils.

*** No data.

(1) extracted by 0.2 M NH₄ oxalate

(2) extracted by citrate-bicarbonate-dithionite Na (CBD)

(3) extracted by 0.5 M NaOH

It is also clear from the data of Table 2 that, in almost all soil samples, Fe extracted by ammonium oxalate (Fe_o) is present in much higher concentrations than Al extracted by the same extractant (Al_o) and the differences were statistically significant (P<0.05). In contrast, the poorly crystalline Fe (Fe_s) was found in smaller concentrations than the Al_s concentrations. The apparent discrepancy between the two extracting solutions, is not possible to be interpreted at present. Furthermore, Fe_d and Al_s concentrations are positively correlated (P<0.05) with the clay content (Figure 2). This is an indication that these Fe and Al compounds fall in size within the clay fraction (Oades, 1989).

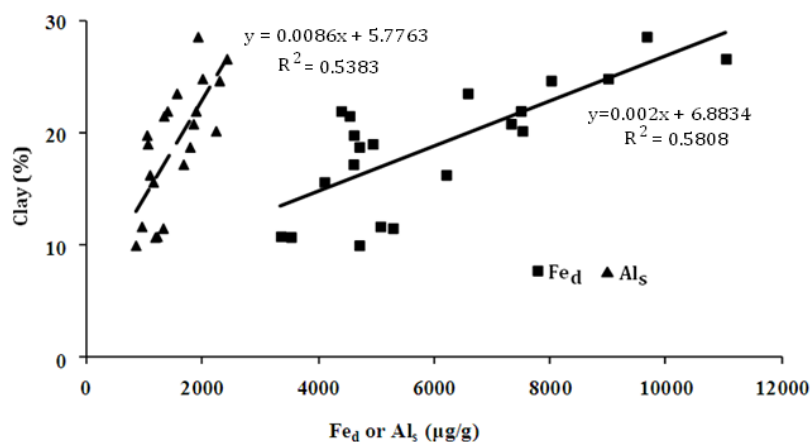


Figure 2. Relationship between crystalline Fe forms (Fe_d), poorly crystalline Al forms (Al_s) and clay content.

Penetration resistance and soil water suction

Figure 3 shows the PR values after equilibration of the soil samples at various soil water suction levels. It is evident that PR of all soils increased with the increase of soil water suction. This is because, by increasing soil water suction, the attractive forces between soil particles (and structural units) also increase and thus soil particles are moved with greater difficulty during the penetrometer entrance in the soil. Moreover, by increasing the soil water suction and the subsequent reduction of soil moisture, the friction coefficient increases between soil particles and structural units, as well as between the soil solid phase and the conical end of the penetrometer.

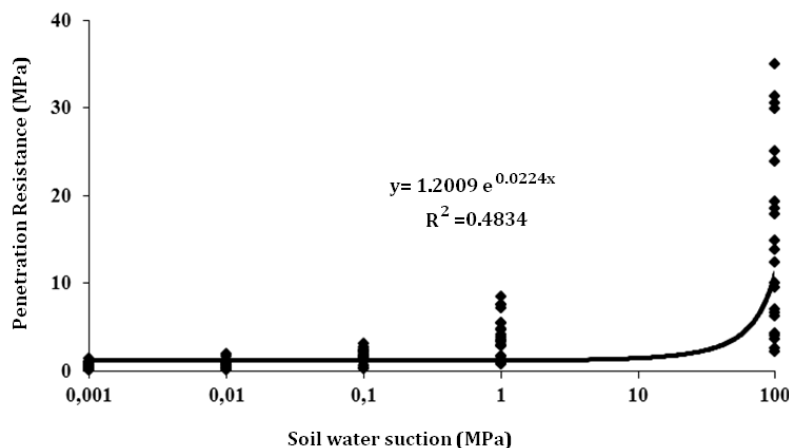


Figure 3. Changes of PR as soil water suction increases.

For each soil sample as well as for all soils, standard deviation (variability) of PR increased as soil water suction increased. This is due to the fact that under unsaturated conditions, the increases of soil water suction (reduction of soil moisture) leads to an increase of the role of the soil solid phase. That is, under these conditions PR variation (increased variability) occurs depending on soil properties.

Additionally, the results showed a general trend of increased PR with depth, probably due to the increasing by depth bulk density (Table 1). However, no statistically significant ($P < 0.05$) relationship was found between these two properties. Greater differentiation between soil horizons is observed at high soil water suction values (≥ 1000 kPa), i.e. at very low soil moisture levels. In contrast, at high soil moisture values (low soil water suction) PR shows almost similar values in all soils and depths, despite differences between bulk density values. These results are in full agreement with data found by Bengough et al. (2001), according to which soil moisture or soil water suction constitutes the major limiting factor for PR determination.

Penetration resistance and Fe and Al oxides and oxy-hydroxides

For the soils of each region separately, positive and statistically significant correlations were found between the mean PR values of the samples and each of the Fe forms obtained by the various extracting solutions. It must be emphasized that the use of the mean PR values has an indicative character and they are given for reasons of comparison. In Figures 4 and 5, the relationships between PR and Fe extracted by citrate-bicarbonate- dithionite sodium (Fe_d) for Halkidona soils and between PR and Fe extracted by 0.5 M NaOH (Fe_s) for Larisa soils, are presented respectively. It appears that the Larisa soils differ from the others in that for a very small increase in the concentration of poorly crystalline Fe, there is a significant increase of PR values. This differentiation is particularly evident in Figure 6 where the regression line between PR and the concentration of free Fe oxides (Fe_d) for the Larisa soils, shows a much steeper slope in relation to the corresponding line of all the other samples. This means that in Larisa soils, free Fe oxides play a more important role in increasing PR than in the other soils. This differentiation is likely due to the greater evolution degree of Larisa soils (Alfisols) resulting in differences in the degree of crystallization, the crystal size of Fe oxides and the nature and properties of clay minerals.

Figure 7 shows the relationship between Fe_o/Fe_d ratio and the mean PR values for Halkidona, Veria and Souroti soils. It appears that the smaller the value of the Fe_o/Fe_d ratio, i.e. the more predominant the free Fe oxides (crystalline forms), the greater the soil PR. Therefore, the significance of the contribution of Fe oxides crystalline compounds on PR and thus on soil strength is obvious. A similar conclusion concerning the

relationship between the values of Fe_o/Fe_d ratio and the PR of soil horizons was reached by Shadfan et al. (1985). In the Inceptisols and Alfisols of Larisa, this trend there was not found.

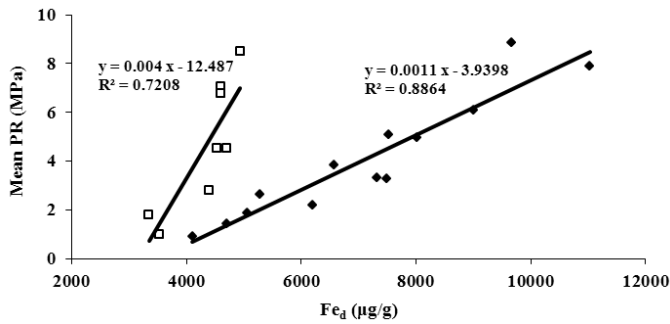


Figure 4. Relationship between mean PR and free Fe oxides and oxy-hydroxides (Fe_d) content in Halkidona soils

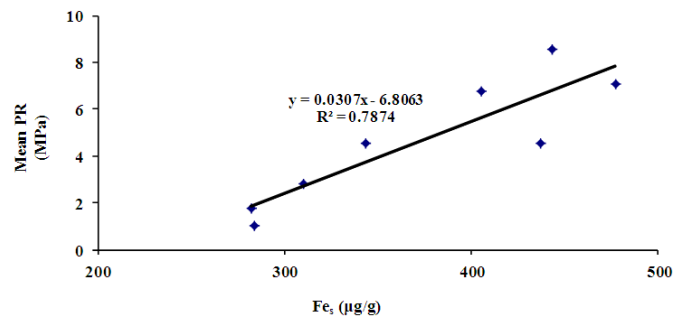


Figure 5. Relationship between mean PR and poorly crystalline Fe forms (Fe_c) content in Larisa soils

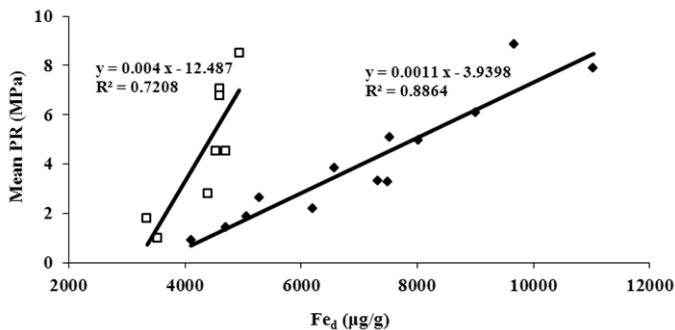


Figure 6. Relationship between mean PR and free Fe oxides and oxy-hydroxides (Fe_d) content in Halkidona, Veria and Souroti soils (as a total, \blacklozenge) and Larisa soils (\square)

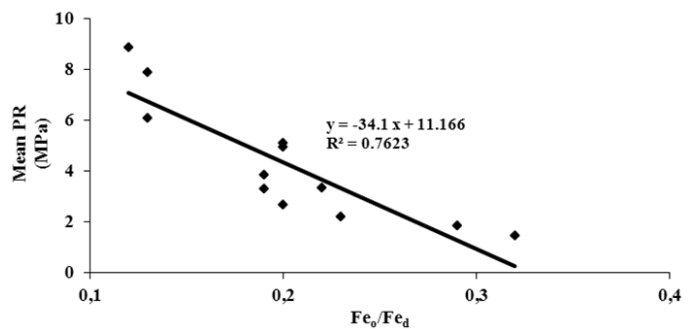


Figure 7. Relationship between mean PR and the Fe_o/Fe_d ratio in Halkidona, Veria and Souroti soils

Regarding the Al compounds extracted by different solutions, there were found no satisfactory relationships between these compounds and PR. The poorly crystalline Al compounds (Al_s) are an exception showing a close and statistically significant correlation with PR in Halkidona, Veria and Souroti soils (Figure 8).

As Fe and Al oxides and oxy-hydroxides play a bonding role and contribute to the hardening of soils, it is natural to expect that their contribution will be cumulative. However, from the results of this study it was found that the correlations between the sum of Fe and Al compounds and PR had no higher correlation coefficient than these compounds separately.

Penetration resistance and clay content

As previously mentioned, there is a convergence of views about the influence of Fe and Al oxides and oxy-hydroxides on PR. Some reviewers (Steel et al., 1969) suggest that these compounds contribute to the increased PR values, while others (Harlan et al., 1977) state that the increased PR is due to the high clay content of soils which also contains increased amounts of Fe and Al oxides and oxy-hydroxides. Regarding the soils used in this study, it was found that the mean PR values correlate with clay content (Figure 9). The R^2 coefficient of this relationship is statistically significant, although not as high as the ones between PR and Fe and Al oxides and oxy-hydroxides content.

The positive and statistically significant relationship between PR and clay is rather expected as statistically significant correlations were also found between clay and Fe and Al oxides and oxy-hydroxides extracted by different extracting solutions (Figure 2). Therefore, from the findings of this study it cannot be said clearly whether and to what extent the increased PR values are due to: a) high Fe and Al oxides and oxy-hydroxides concentrations, b) the high clay content in soils, or c) a combination of these two soil components. The predominance of Fe and Al oxides or clay on PR could be fully clarified using pure systems.

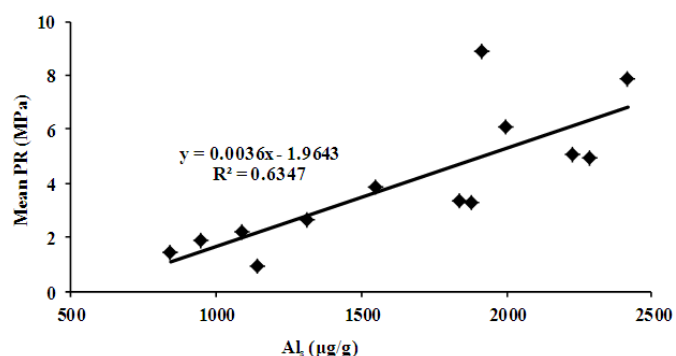


Figure 8. Relationship between mean PR and poorly crystalline Al oxides and oxy-hydroxides (Al_s) content in Halkidona, Veria and Souroti soils

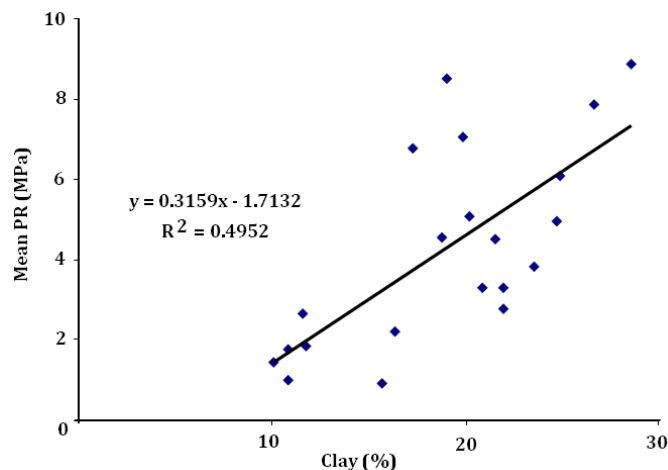


Figure 9. Relationship between mean PR and clay content in all the soils used

Conclusion

The findings of this study can be summarized as follows:

There is a statistically significant positive correlation between iron and aluminum oxides and oxy-hydroxides as well as the clay content (%) and PR. However, it is not entirely clear which of the two soil components plays the most important role in PR changes in soils.

There is a statistically significant negative correlation between the Fe_o/Fe_d ratio and PR. This is a strong evidence for the significant contribution of free (crystalline) Fe oxides and oxy-hydroxides on PR.

Additional research effort is required, using pure systems to fully clarify the role of clay, Fe and Al oxides and oxy-hydroxides and possibly other adhesive components on soil PR.

Soil type (Entisol, Inceptisol, Alfisol) and its evolution degree seem to play a significant role in the relationship between PR and free iron oxides and oxy-hydroxides.

Acknowledgments

I would like to thank Professors K.P. Panayiotopoulos and N. Barbayiannis, Soil Science Laboratory, Aristotle University of Thessaloniki, for their help in soil samples analysis.

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