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Variation of physical and mechanical properties with depth in Alfisols

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Abstract. Physical and mechanical properties (particle and aggregate size distribution, aggregate stability, bulk density, pores size distribution, air-capacity, water retention, saturated hydraulic conductivity, shrinkage, plastic and liquid limit and drop-cone penetration) influence soil productivity and determine soil management practices and land use planning. These properties have being determined *in situ* or on samples collected from depths of 0-10, 25-35 and 50-60 cm of three Alfisols from the Northern Greece. The soils differed both in particle size distribution and clay mineralogy. These differences have being reflected in changes of the physical and mechanical properties studied, both between and within soils. These changes could not be explained by particle size distribution and clay mineralogy alone. A high content of Al oxides and hydroxides, found in these soils contributing to aggregate formation and stabilisation, may also affect most of the properties studied. Some of the physical and mechanical properties were found to be interrelated to one another. For most of the cases, close correlations were obtained between these properties and some soil constituents, such as clay, sand, organic matter, CEC and Al oxides and hydroxides. The effect of various physical and mechanical properties on plant root development and soil genesis and degradation is discussed.

Keywords: Alfisols, physical properties, mechanical properties

INTRODUCTION

Soil physical and mechanical properties are the most important factors affecting soil productivity. These properties include particle size distribution, aggregate size and stability and pore size and continuity, which in turn determine water retention and flow, soil aeration and temperature, shrinking-swelling, plasticity and strength. All the above properties influence root system growth and development (Gliñski and Lipiec, 1990) while some of them determine soil susceptibility to both compaction (Horn and Lebert, 1994) and erosion (Larson and Padilla, 1990) and soil suitability for reduced tillage and direct drilling (Stengel *et al*., 1984). Therefore, information related to soil physical and mechanical properties are very important when considering design of management practices for crop production and soil conservation. Since roots extend well below the surface layer, physical and mechanical properties have to be known down to the effective rooting depth. Determination of the above mentioned properties is, in most cases, labour and time consuming due to the large number of measurements necessary either in the field or in the laboratory. However, some physical and mechanical properties can be predicted if some others or easily determined chemical properties are known (Smith *et al*., 1985; Wösten, *et al*., 1998).

Alfisols make up nearly 15% of the world soils, much more in the temperate zone, but not much information is available on their physical properties, the relation between physical and chemical properties and their effect on plant growth and soil formation. Thus, the aim of this paper was: i) to study changes in the basic physical and mechanical properties with depth in three representative non-cultivated Greek Alfisols, ii) to explain relationships between the above properties and iii) to give an insight on the influence of these properties on plant growth and soil management practises as well as on the soil genesis and degradation.

MATERIALS AND METHODS

Undisturbed and disturbed soil samples were taken from the surface (0-10 cm) and from depths of 25-35 and 50-60 cm at three locations in the Northern Greece, namely Kerasia, Xyloupoli and Galatista. The depths of 25-35 and 50-60 cm were chosen as they are the depths just below the ploughing layer and relevant to the effective rooting depth

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*Corresponding author's e-mail: kpp@agro.auth.gr of main crops. The selection of soils (i.e. Alfisols (Soil Survey Staff (1975)) was based mainly on their abudance under Mediterranean conditions and on their varied parent material; All of them were under natural vegetation.

Dithionite-extractable Fe and Al oxides and hydroxides were determined by the method by Mehra and Jackson (1960) while cation exchange capacity (CEC) was determined according to Chapman (1965). Clay minerals were determined by a semi-quantitative analysis (Jackson, 1970).

Particle size distribution was determined by the pipette method (Day, 1965). Aggregate size distribution after dry and wet sieving was conducted on <6.35 mm aggregates (Kemper and Chepil, 1965).

For the soil water characteristics, the cores (five replicates) were vacuum-saturated (2-3 kPa) in deaired 0.005 M $CaSO_4$ solution. $CaSO_4$ solution was used in order to minimize clay dispersion and the consequent structure alteration. After saturation, the samples were left to equilibrate at progressively increasing matric suctions from 1 to 1000kPa. The sample equilibration was obtained by means of i)a tension table for the matric suctions of 1, 2, 4 and 10kPa and ii)a pressure plate apparatus for the matric suctions of 33, 100 and 1000kPa. After equilibration at a given matric suction, the samples were removed, weighed and the next higher matric suction was applied. After equilibration at 1000kPa matric suction, the samples were weighed, oven dried and reweighed and the dry mass of each sample was determined. Next, water content (on a dry mass basis) at any matric suction was calculated. For matric suctions of 10000, 50000 and 100000kPa, disturbed soil samples were put in airtight chambers in which relative humidity was equal to 92.9, 75.6, and 46.8%, respectively. The relative humidity values were kept constant by having in the chambers H_2SO_4 solutions of a concentration equal to 15, 30 and 45%v/v (Childs, 1969). After equilibration, the samples were weighed, oven dried and reweighed and the water content of each sample was determined.

Bulk density was determined by the core method in five replicates (Blake and Hartge, 1986). Total porosity was assumed to be equal to the water content (v/v) at saturation. Pore size distribution was calculated from drainable porosities at various matric suction levels applied using the capillary rise equation. Air-capacity, n_a, was calculated as $n_a = n - \Theta_{10}$, where: n is total porosity and Θ_{10} is the water content (v/v) at 10 kPa matric suction.

Saturated hydraulic conductivity was measured *in situ* using a constant head permeameter (Reynolds and Elrick, 1986) and five measurements were taken within a radius of 1 m of the sampling point. Deaered 0.005 M $CaSO_4$ solution was used as the test fluid (Klute and Dirksen, 1986).

Liquid and plastic limits were determined by the methods suggested by Campbell (1975, 1976), whereas linear shrinkage was measured according to the British Standards (British Standard 1377, 1975). Plastic limit, liquid limit and linear shrinkage were determined on three replicates.

Drop-cone penetration was determined on undisturbed soil samples equilibrated at 0, 1, 10, 100, 1000 and 10^5 kPa matric suction. Three replicates were used and 5-7 penetrations were made on each sample. A Wykeham Farrance Eng drop-cone penetrometer with a cone mass of 0.08 kg and a cone angle equal to 30° was used for the measurements. The t-test was used for statistical analysis.

RESULTS AND DISCUSSION

Chemical properties and clay mineralogy

Parent materials and classification of the soils used as well as chemical properties and clay mineralogy are presented in Table 1. At any depth of the soils studied, they were mostly acidic, low in organic matter and $CaCO_3$ and with high content of dithionite-extractable Fe- and Al-oxides and hydroxides (Fe_d and Al_d, respectively, Table 1) which increased with depth. The high Fe_d and Al_d content is considered responsible for the physical behaviour of these soils since these oxides determine both particle aggregation (Kostopoulou and Panayiotopoulos, 1993) and aggregate stability (Panayiotopoulos and Kostopoulou, 1989). It is also worth noting that both in the Xyloupoli and Galatista soils micas predominated between clay minerals followed by kaolinite while the clay fraction of Kerasia soil consisted mainly of montmorillonite and micas.

Particle size distribution

The content of gravels and stones did not exceed 10% (w/w) in any of the soils studied. Clay content increased with depth in all soils and it was found to decrease in the following order: Kerasia, Xyloupoli, Galatista (Table 2). Significant differences in the mean clay content were found both between and within the soils. The same picture was also true for fine clay (<1 m) which increased with depth in all soils and represented a high percentage (66-85.7%) of the clay content. The fine clay/clay ratio was also found to increase with depth. In the Kerasia and Galatista soil silt increased and sand decreased with depth while in the Xyloupoli soil silt decreased and sand increased with depth. As can be seen below, these differences in particle size distribution with depth between soils along with differences in clay mineralogy, mentioned earlier, are to be reflected to some physical and mechanical properties.

Aggregate size and stability

Both the mean weighed aggregate size after dry sieving ($MWAS_d$) and the mean weighed aggregate size after wet sieving ($MWAS_w$) were found to increase with depth and in most cases significant differences ($p<0.05$) of both $MWAS_d$ and $MWAS_w$ were observed between the depths of each soil (Table 2). $MWAS_d$ decreased in the following order: Kerasia, Xyloupoli, Galatista and significant differences

Table 1. Selected chemical properties and clay mineralogy of the soils

Depth	pH	E.C.	C.E.C.	O.M.	Fe_d	Al_d	$CaCO_3$	s*	i	v	k	c	q
(cm)		(dS m^{-1})	(mmol$_c$ kg^{-1})	(%)	(g kg^{-1})			(%)					
Typic Haploxeralf from soft calcareous deposits, Kerasia													
0-10	7.25	0.155	252	11.7	12.1	6.21	5.7	30	40	5	10	-	15
25-35	6.75	0.118	343	7.22	11.8	6.73	5.4	45	35	-	5	-	15
50-60	7.72	0.314	338	5.16	15.5	7.60	11.3	40	30	-	5	5	20
Ultic Palexeralf from granitic gneiss, Xyloupoli													
0-10	5.80	0.127	203	28.3	21.6	2.71	6.3	>5	80	-	10	-	-
25-35	5.75	0.125	228	12.7	25.6	3.27	4.4	>5	70	-	20	-	-
50-60	5.95	0.177	174	8.49	25.1	3.16	4.9	-	60	-	40	-	-
Typic Rhodoxeralf from phyllite, Galatista													
0-10	5.80	0.177	87	14.8	16.1	3.03	-	<5	50	-	30	5	10
25-35	5.80	0.104	123	4.24	24.2	4.28	-	-	60	-	20	-	20
50-60	5.90	0.086	131	3.81	27.6	4.99	-	-	60	-	20	-	20

*s – smectite, i – illite, v – vermiculite, k – kaolinite, c – chlorite, q – quartz.

Table 2. Particle size distribution (g kg^{-1}), mean weighed aggregate size after dry ($MWAS_d$) and after wet ($MWAS_w$) sieving and aggregate stability (AS) of the soils

Depth (cm)	Sand 2000-50 m	Silt 50-2 m	Clay <2 m	Fine clay <1 m	$MWAS_d$ (mm)	$MWAS_w$ (mm)	AS (%)
Kerasia							
0-10	566a*	136ab	298a	238a	2.56a	2.02ab	80a
25-35	487a	174a	339a	272a	2.70b	2.42a	85b
50-60	406a	1184b	410a	342a	2.97ab	2.64b	90a
Xyloupoli							
0-10	565a	191a	244a	161a	2.02ab	1.96a	90a
25-35	485a	246a	269a	181b	2.70a	2.15	90b
50-60	423a	280a	297a	229ab	2.84b	2.64ab	95c
Galatista							
0-10	577a	290ab	133a	91a	1.83ab	1.68a	84a
25-35	421a	320a	259a	190a	2.58a	2.24a	86b
50-60	359a	315b	326a	279a	2.82b	2.54a	91a

* Means followed by the same letter are significantly different at <0.05. Letters can only be compared within a column and soil.

($p<0.05$) were obtained between the soils. $MWAS_W$ was also found to decrease in the same order as $MWAS_d$, but significant differences ($p<0.05$) were observed only between the Galatista and any one of the other two soils. The difference between $MWAS_d$ and $MWAS_W$ expresses a different resistance offered by attractive forces and bonds within the aggregates under dry and wet conditions, respectively. $MWAS_d$ is an important property as it determines aggregates susceptibility to movement (erosion) and because it influences pore size (Kemper and Chepil, 1965). On the other hand, the $MWAS_W$ is a measure of the resistance offered by the aggregates against slaking and sealing. Therefore, any relation between these two important properties and any easily determined soil properties would be very helpful for predicting $MWAS_d$ and $MWAS_w$. Actually, $MWAS_d$ and $MWAS_w$ were found to correlate significantly ($p<0.05$) with clay ($r=0.89$ and $r=0.85$, respectively) while no significant correlation was obtained between these properties and either organic matter (OM) or Fe_d and Al_d. However, in an attempt to elucidate the factors affecting $MWAS_d$ and $MWAS_w$ step-wise multiple regression was used and the following relationships were obtained:

$$MWAS_d=1.16+0.008\ clay-0.167Al_d-0.023OM,\quad R^2=0.92,\ p<0.001$$

$$MWAS_w=1.39+0.002\ clay-0.002\ sand+0.013AS,\quad R^2=0.83,\ p<0.001$$

where: AS stands for aggregate stability. It is suggested that the presence of organic binding agents (e.g., polysaccharides) and cation bridges results in the formation of small-sized aggregates (Hamblin, 1985). On the other hand, Panayiotopoulos and Kostopoulou (1989) proposed that in soils similar to those used in this work, the primary and secondary structural units of the Edwards and Bremner (1967) model [C-P-OM and $(C\text{-}P\text{-}OM)_x$, where: C is clay and P is a cation bridge] are held together and stabilised to larger structural units by Fe_d and Al_d. Furthermore, it was found that particle size distribution plays an important role in the aggregate size (Panayiotopoulos and Kostopoulou, 1989). In addition, $MWAS_w$ may be influenced by aggregate stability. From the above relations it seems that different factors determine the MWAS under dry and wet conditions. That is, while under dry conditions OM and Al_d play an important role to aggregate size. Under wet conditions their effects apparently disappeared and thus $MWAS_w$ depends on clay and sand content (both of which determine the packing of soil material) and on AS. However, Panayiotopoulos and Kostopoulou (1989) found for similar soils, that AS was depended on Al_d. Therefore, it seems that the influence of Al_d on $MWAS_w$ was obscured by the overall effect of AS on $MWAS_w$. $MWAS_w$ and $MWAS_d$ were found to be interrelated by the relationship:

$$\ln MWAS_w=0.169+0.254MWAS_d,\ R^2=0.82,\ p<0.001.$$

Aggregate stability of all soils and depths studied was high (Table 2) as compared to other soils covering a variety of textures (i.e., Stengel *et al.*, 1984) and a trend of increasing AS with depth was evident. However, if all soils were considered together, significant differences ($p<0.05$) in AS have been observed only between 50-60 cm depth and the other two depths studied.

Aggregate stability is usually attributed to clay and OM content, but in Alfisols Fe_d and Al_d play also an important role in aggregate stabilisation (Schwertmann and Taylor, 1987). In the soils used, OM decreased and clay, Fe_d and Al_d increased with depth (Table 1). Consequently, their additive effects on AS varied between soils as well as within each soil with depth. Pressure alone cannot promote particle aggregation and stabilisation, but if it is combined with the presence and action of cementing agents, pressure may play some role in the aggregate stability (Hillel, 1998). Thus, stable aggregate formation is a complex process in which several factors play a role. Therefore, any attempt to relate the AS of all soils and depths to any single stabilising factor is probably meaningless. A step-wise multiple regression was therefore applied and it yielded the following relationship:

$$\text{Aggregate stability}=68.82+1.60OV+0.49(Fe_d+Al_d),\quad R^2=0.68,\ p<0.001$$

where: OV stands for an overburdened load (kN m^{-2}) calculated as bulk density times acceleration due to gravity times depth.

Bulk density, pore size distribution and air-capacity

The bulk density (BD) of the surface layer was always smaller than that at the other two depths (Table 3). A higher OM content (Table 1), an increased biological activity near the surface and the corresponding smaller aggregate size (Table 2) can explain the more ‘open’ structure and a consequently smaller BD at the surface of the soils. In the Xyloupoli soil, BD increased with depth while in the Kerasia and Galatista soils the highest BD were observed at the intermediate depth. BD changes with depth can be explained by different variations in the particle size distribution with depth between the soils (Table 2) which resulted in the different packing of soil particles (Panayiotopoulos, 1989). Significant differences ($p<0.05$) in BD were found between the Xyloupoli and the other two soils. For all soils taken collectively, significant differences ($p<0.05$) in BD were found between the surface layer and the other two depths. BD and OM content were linearly correlated to each other ($r=-0.77$, $P<0.05$).

In all soils, the lowest percentages of macropores (>100 μm) existed at the intermediate depths (Table 3), although for both the Kerasia and the Xyloupoli soils no significant difference ($p<0.05$) in the macropore percentage were found between the depths of 25-35 and 50-60 cm. The macropore percentage varied in an opposite direction than BD and a significant correlation ($r=-0.77$, $P<0.05$) between these two properties was obtained. Mesopores (30-100 μm) decreased while micropores (<30 μm) increased with depth in all soils (Table 3). An increase of micropores with depth can be explained by the denser packing of soil particles due to the increase of clay and fine clay content with depth as well as to the soil overburden above. Pore size distribution is considered to be the best indication of soil structure condition since it determines the very important physical properties such as water retention and flow and soil aeration and temperature. Furthermore, pore continuity and proportion of

Table 3. Bulk density, porosity, macropores (>100 m), mesopores (30-100 m), micropores (<30 m), air-capacity and hydraulic conductivity (K_s) of the soils

Depth (cm)	Bulk density (Mg m^{-3})	Porosity (m^3 m^{-3})	Macropores*	Mesopores*	Micropores*	Air-capacity (m^3 m^{-3})	K_s (m s^{-1})
				Kerasia			
0-10	1.315a**	0.501a	23.0ab	14.9ab	62.1ab	0.19ab	1.20a
25-35	1.591a	0.400a	6.0a	9.7a	84.3a	0.05	0.31a
50-60	1.496a	0.435a	7.5b	6.0b	86.5b	0.06b	-
				Xyloupoli			
0-10	1.251ab	0.528ab	22.5ab	12.4a	65.1ab	0.19ab	0.20a
25-35	1.317a	0.503a	14.0a	9.2b	76.8a	0.12a	0.07a
50-60	1.354b	0.489b	16.0b	8.5c	75.5b	0.13b	-
				Galatista			
0-10	1.335a	0.496a	26.0a	30.6a	43.4ab	0.30ab	47.3a
25-35	1.590a	0.400a	10.0ab	21.1b	68.9a	0.13a	1.06a
50-60	1.461a	0.449b	20.0b	10.4a	69.6b	0.16b	-

*As a percentage of porosity, **Means followed by the same letter are significantly different at P<0.05. Letters can only be compared within a column and soil.

macropores are considered important for adequate root growth and activity (Atkinson and Dawson, 2001).

The highest values of air-capacity appeared at the 0-10 cm depth (Table 3) and the smallest at the intermediate depths although the latter did not differ significantly with the corresponding values at 50-60 cm. Significant differences ($p<0.05$) of air-capacity were found between soils as well as between the surface layers and the other two depths taken collectively. Air-capacity was in most cases greater than the critical level of 0.1 m^3 m^{-3} for adequate soil aeration and the consequent biological activity (Stêpniewski *et al*., 1994). Under such conditions oxidation rather than reduction may prevail and chemical weathering will further proceed.

Water retention and hydraulic conductivity

As may be seen from Fig. 1, water retained at matric suctions greater than 1 kPa increased with depth. It is also clear that Kerasia and Xyloupoli soils retained almost equal amount of water at any matric suction although Kerasia soil contains more clay and smectite predominated in its clay fraction. This can be explained by a larger Al_d content of the Kerasia soil (Table 1) which binds clay particles and therefore prevents smectite swelling and the subsequent increased water absorption. The Galatista soil, containing less clay and organic matter than the other two soils, retained less water at any matric suction.

Saturated hydraulic conductivity (K_s) was found to decrease with depth in all soils and significant differences ($p<0.05$) in K_s were observed between soils and depths (Table 3). When all soils were considered together, K_s was linearly and closely ($P<0.05$) related to the clay content ($r = -0.87$). However, the best relation between K_s and any single soil property found in this work was expressed by the equation:

$$\log K_s = -1.89 + 23.05 n_{30},\ R^2=0.89,\ p<0.001$$

where: n_{30} is a fraction of total porosity consisting of pores >30 m in diameter, (i.e., macropores + mesopores). The above relationship describes very well the dependence of K_s on pore size and as it may account for at least 89% of the variance of K_s, it can be used for predicting K_s of similar soils, if pore size distribution is known, assuming a similar pore continuity. Similar results were reported by Southard and Buol (1988) for a variety of soils. Significantly higher K_s values obtained in the Galatista topsoil will result in a higher leaching and in faster soil-formation processes as well as in limited run-off and the consequent water erosion.

Plastic limit, liquid limit and shrinkage

A trend towards an increasing plastic (PL) and liquid (LL) limits with depth was observed and significant differences ($p<0.05$) in both PL and LL were found both between and within soils (Table 4). The following relationships have been found for the PL and the LL:

$$PL = 25.73 - 0.035\,\text{sand} + 0.027\,CEC + 0.2\,OM,\quad R^2=0.75,\ p<0.001$$

$$LL = 51.39 - 0.029\,\text{sand} + 0.03\,CEC,\ R^2=0.76,\ p<0.001.$$

Both PL and LL depend mainly on the particle size distribution, clay mineralogy as well as on the cementing agent present (Yong and Warkentin, 1975). Clay content

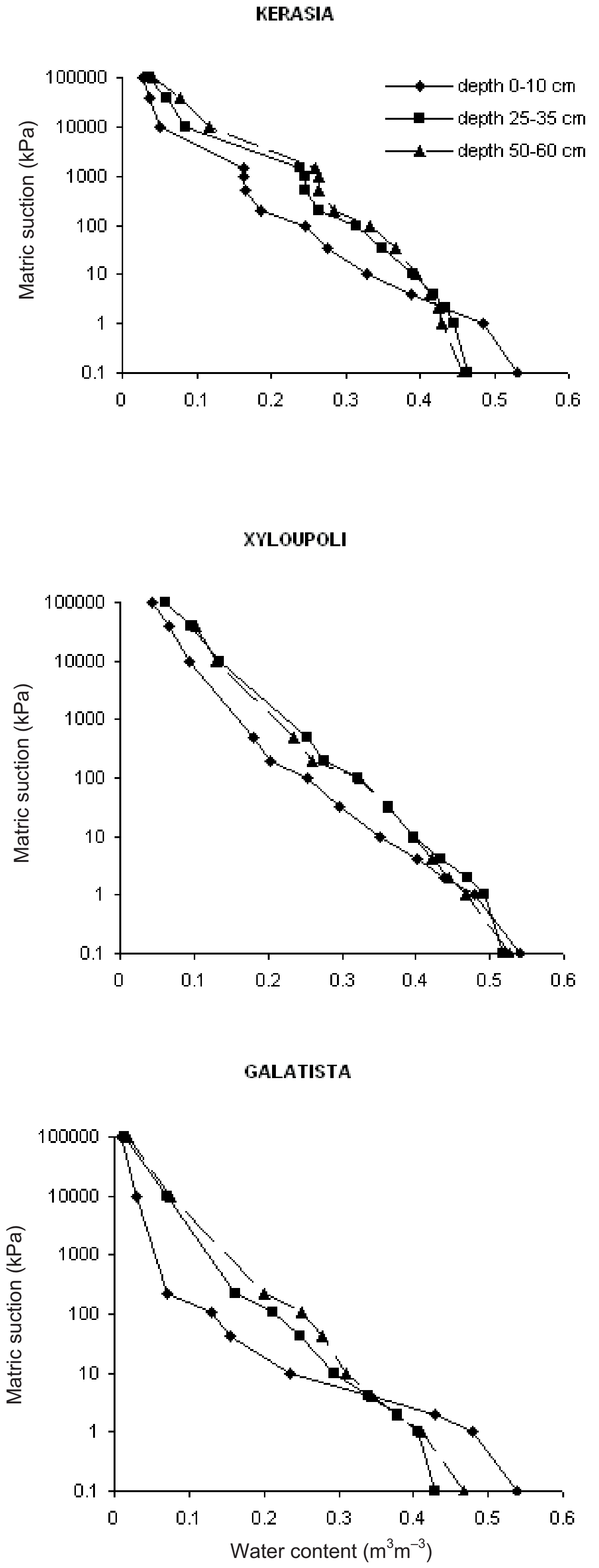

Fig. 1. Water retention curves.

and mineralogy as well as OM content were reflected here in CEC. A further influence of OM on PL shown in the relationship given above, can be attributed to extra water that OM must absorb in order to allow for the soil particles to move or slide past one another and the soil to change its state from a friable or brittle to a plastic one (Yong and Warkentin, 1975).

PL and LL provide information concerning soil workability and potential for structural damage. Tillage of the soil at water contents greater than the PL may cause smearing and soil compaction (Campbell *et al.*, 1980). Since after rain or irrigation the first 'equilibrium water content' is field capacity (FC), any relationship between FC and PL should be very useful. In this study, volumetric water content at 10 kPa water tension (corresponding to FC) was always greater than the PL. Therefore, these soils should dry more than at FC in order to give an optimum moisture range for tillage operations. The equations relating PL and LL to FC are as follows:

$$\mathrm{PL} = -3.00 + 0.577\mathrm{FC},\ R^2=0.81,\ p<0.001$$

$$\mathrm{LL} = 24.08 + 0.577\mathrm{FC},\ R^2=0.83,\ p<0.001$$

while: PL and LL were found to be interrelated by the relationship:

$$\mathrm{PL} = -26.08 + 0.974\mathrm{LL},\ R^2=0.97,\ p<0.001.$$

Linear shrinkage was found to decrease in the following order: Kerasia, Xyloupoli, Galatista and significant differences ($p<0.05$) were observed between the Galatista and the other two soils (Table 4). A trend towards an increasing linear shrinkage with depth was also observed. The above changes can be attributed to differences in particle size distribution, clay mineralogy and in the content of binding and stabilising agents (e.g., OM, $\mathrm{Al_d}$ and $\mathrm{Fe_d}$) both between and within soils. Linear shrinkage was found to correlate very closely ($r=0.92$, $P<0.01$) with clay content. This correlation was improved when $\mathrm{Al_d}$ was also introduced to the regression equation and the following relationship was obtained:

$$\text{Linear shrinkage} = -2.79\text{-}0.96\mathrm{Al_d}+0.058\ \text{clay},$$
$$R^2=0.93,\ p<0.001.$$

It is well established that $\mathrm{Al_d}$ contribute to particle aggregation and stabilisation and their effect is more pronounced than $\mathrm{Fe_d}$ (Panayiotopoulos and Kostopoulou, 1989). Thus, the existence of $\mathrm{Al_d}$ in soils resulted in an impedance of particles to approach very close to one another during drying. If this is the case, $\mathrm{Al_d}$ may have a negative influence on the linear shrinkage as it was found in the above relationship. Linear shrinkage at the surface layer of the Galatista was much less than that of the Kerasia and Xyloupoli soils (Table 4). This will result in less cracking in

Table 4. Plastic limit, liquid limit and linear shrinkage of the soils

Depth (cm)	Plastic limit	Liquid limit	Linear shrinkage
		(%)	
		Kerasia	
0-10	15.1a	42.0a	8.7a
25-35	15.9b	43.2b	10.1a
50-60	21.2ab	48.1ab	14.7a
		Xyloupoli	
0-10	19.0a	43.3ab	8.8a
25-35	20.1b	48.8a	9.7b
50-60	22.3c	49.0b	12.2ab
		Galatista	
0-10	9.0ab	37.1ab	2.4a
25-35	14.0a	42.2a	7.3a
50-60	16.1b	43.9b	9.7a

*Explanations as in Table 2.

the Galatista soil during drying and consequently in smaller changes in pore size and continuity, aeration, temperature regime, evaporation of soil water and soil strength.

Drop-cone penetration

Drop-cone penetration decreased linearly as matric suction increased (Fig. 2). Similar results have been suggested by several authors (e.g., Campbell and Hunter, 1986; Schjonning, 2000) for the soils covering a variety of textures. From Fig. 2 it is also seen that the penetrations of the topsoil samples were much greater than those taken from the other two depths studied. This differentiation may be seen as a consequence of the more ‘open’ structure (i.e., smaller MWAS, higher porosity, smaller percentage of micropores, etc.) at the surface. Significant differences ($p<0.05$) in penetration were observed only between the samples taken from the surface and those taken from the other two depths. Thus, all samples could be considered as belonging to two groups, one consisting of surface samples and the other consisting of samples collected from depths of 25-35 and 50-60 cm. When drop-cone penetration, h, of the surface samples was correlated against the logarithm of soil water matric suction (SWMS), a very close relationship was obtained (Fig. 2):

$$h=8.147–0.693\log SWMS,\ R^2=0.73,\ p<0.001.$$

A similar relationship was also found for samples taken from the 25-35 and 50-60 cm depth (Fig. 2):

$$h=3.32–0.251\log SWMS,\ R^2=0.70,\ p<0.001.$$

From the above two relationships it is clear that soil water matric suction is the dominant factor determining penetration, although the soils used differ in most of the properties studied.

The significantly different ($p<0.05$) penetration observed at matric suctions of up to 1000 kPa between the surface layer and the other two depths of all soils will influence the growth and development of plant roots. Thus, while the roots can penetrate into the surface layer very easily, their development may be retarded at depths >25 cm.

Hansbo (1957) undertook drop-cone tests on remoulded clays in the laboratory and showed that non-drained shear strength, S, was related to drop-cone penetration by the equation:

$$S = KQ/h^2 \tag{1}$$

where K is a constant and Q is cone mass. Towner (1973) showed that K varied with soil texture and that although shear varied inversely with the penetration square for plastic soils, the power to which h should be raised might be slightly less for sands. Mullins and Fraser (1980) found that although K values for remoulded cores were comparable to those obtained by Towner (1973), they were several times larger than the corresponding K values for the undisturbed cores. Wood (1985) suggested a constant K value (=0.85) for cones with a 30° angle. In addition, Campbell and Hunter (1986) found that correlation coefficients between vane shear strength and penetration, h, were greater than those obtained between vane shear strength and $1/h$ or $1/h^2$. It seems therefore, that Eq. (1), which was originally derived for remoulded clays, does not apply to field soils, since the equation makes no allowance for factors such as structure, organic matter, plant roots, etc. (Campbell and Hunter, 1986). Therefore, no attempt was made in this work to calculate soil shear strength from the drop-cone penetrations results.

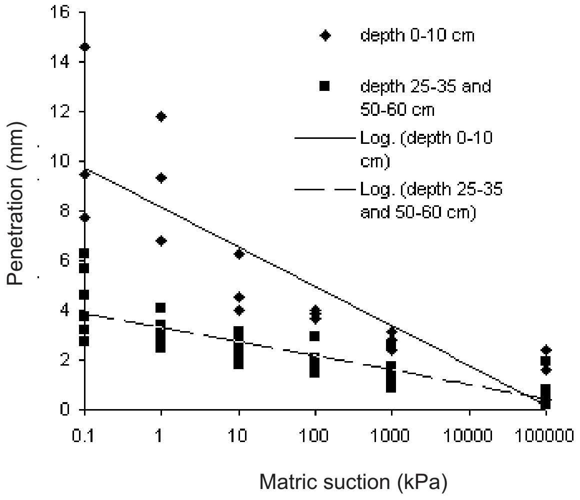

Fig. 2. Drop-cone penetration versus soil water matric suction.

CONCLUSIONS

The main conclusions of this work are summarised as follows:

1. A change in particle size distribution both between and within soils along with the variations in clay mineralogy, organic matter, Fe and Al oxides and hydroxides content, influence all the physical and mechanical properties of the soils studied.

2. Mean weighed aggregate size obtained after dry and after wet sieving, aggregate stability, water retention, plastic and liquid limits and linear shrinkage were found to increase while saturated hydraulic conductivity and drop-cone penetrations were decreased with depth.

3. No clear trend of variation with depth was observed for bulk density, pore size and air-capacity. In most cases the above properties were significantly different ($p<0.05$) between soils and depths. However, the difference in physical properties between soils and depths observed in this work, were not very large as one would expect based on the differences in particle size distribution and clay mineralogy only. This can be explained by the high Al oxides and hydroxides content which contribute to aggregation of soil particles and to stabilisation of aggregates and thus giving to the soils a different behaviour.

4. In most cases significant correlations were obtained between physical and mechanical properties. Close relationships were also found between physical or mechanical properties and simply determined soil properties and soil constituents.

5. A change of physical and mechanical properties observed both between and within the soils will be reflected to both root development and plant growth. In addition, changes in these properties will influence soil forming processes (e.g., leaching, weathering) and soil degradation to a different manner.

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