EFFECT OF BULK DENSITY ON HYDRAULIC PROPERTIES OF HOMOGENIZED AND STRUCTURED SOILS

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Efecto de la densidad aparente sobre las propiedades hidráulicas de los suelos homogenizados y estructurados

Keywords: Water retention curve, soil shrinkage, soil structure

ABSTRACT

In order to determine the effect of bulk density and soil structure on their hydraulic behaviour, undisturbed samples were collected and disturbed samples were prepared from a Luvisol. The experimental field, located in Harste/Goettingen, Germany, was cultivated with sugar beet (Beta vulgaris). The water retention curve (WRC) and saturated hydraulic conductivity (Ks) were measured on undisturbed samples and homogenized samples prepared at different bulk densities (1.2 -1.4 and 1.6 Mg m^{-3}). To determine the effect of soil shrinkage on the unsaturated hydraulic conductivity (k/ψ), the vertical deformation of the repacked samples was measured and relative water content differences ($d\theta$)were determined. The hydraulic properties of soils with identical texture depend on bulk density (d_B) and structure. The increasing bulk density not only induces changes in the pore-size distribution but also affects the ability of soil to shrink and to conduct water under unsaturated conditions. Greater shrinkage was observed for samples with lower d_B as a consequence of reduction of coarse pores. The water content differences increase with decreasing bulk density, inducing an increasing error in the estimation of k/ψ.

Palabras clave: Curva de retención de agua, contracción suelo, estructura suelo

RESUMEN

Con el objetivo de determinar el efecto de la densidad aparente y estructura del suelo sobre su comportamiento hidráulico, muestras no disturbadas fueron recolectadas y muestras disturbadas fueron preparadas a partir de un Luvisol. El campo experimental, ubicado en Harste/Goettingen, Alemania, fue cultivado con remolacha (*Beta vulgaris*). La curva de retención de agua (WRC) y la conductividad hidráulica saturada (Ks) fue determinada en muestras no disturbadas de suelo y en muestras homogenizadas preparadas a distintas densidades aparentes (1.2 -1.4 y 1.6 Mg m^{-3}). Para determinar el efecto de la contracción del suelo sobre la conductividad hidráulica no saturada (k/ψ), se midió la deformación vertical de las muestras ensambladas y a partir de ello se determinó la diferencia en el contenido volumétrico de agua.

Las propiedades hidráulicas de suelos con la misma textura dependen de la densidad aparente y la estructura. El incremento en la densidad aparente no sólo induce cambios en la distribución de la porosidad sino que también afecta la capacidad de contracción del suelo y de conducir agua en fase no saturada. Una mayor contracción fue observada en muestras con menor densidad aparente como consecuencia de la reducción de los poros gruesos. Las diferencias en el contenido de agua aumentan con una disminución en la densidad aparente, induciendo un mayor error en la estimación de (k/ψ).

INTRODUCTION

Soil hydraulic properties like the retention capacity and hydraulic as well as gas conductivity have agronomical and ecological implications. Drainage, evaporation and water-uptake by roots are just few examples where the knowledge about the rate of water flow through the soil plays an important role (Plagge *et al*., 1990; Kutilek and Nielsen, 1994).

The relative proportion of the three phases (water, gas and solid) of the soil is influenced by properties like texture, structure, biological activity, weather and soil management (Hillel, 1998). In these terms the porous media can be characterized in their volume and function which is of great relevance to understand processes related to water, air and heat transport in soils (Oschner *et al*., 2001; Dörner and Horn, 2006).

Soil volumes are affected by mechanical stresses (e.g. tillage-induced soil compaction, Blackwell *et al*., 1986; Horn et al., 1991; Horn et al., 1995; Ball *et al*., 1997; McNabb *et al*, 2001) and internal forces (e.g. wetting and drying cycles, Peng and Horn, 2007; Bartoli *et al*., 2007). The magnitude of volume changes are controlled by the mechanical stability of the soil or by the level of the actual in comparison with previous internal stresses. The internal stresses in soils containing more than 12% of clay induce aggregate formation, which results firstly in a prismatic structure with a dominant vertical pore function orientation. Repeated swelling and shrinkage creates tensile and shear induced crack formation in blocky and thereafter in a subangular blocky structure (Horn and Smucker, 2005).

The effects of soil compaction on soil structure have been investigated by many authors (Blackwell *et al*., 1986; Horn *et al*., 1995; Ball *et al*., 1997; McNabb *et al*., 2001). It is also well known that soils are able to shrink and swell (Peng *et al*., 2006). However, with respect to the calculation of hydraulic properties, it is always assumed that soils behave like a rigid body. Soil shrinkage can be characterized by the shrinkage curve, which relates the volume changes as a function of the water content changes. The shrinkage curve generally presents a typical sigmoidal shape; with linear and curvilinear parts determining successive phases of shrinkage. Bronswijk (1990) defined these phases from the wet to the dry side as: structural shrinkage, normal shrinkage, residual shrinkage and zero shrinkage. These zones differ between each other from the relative proportion of water losses and volume decrease being both proportional in the normal shrinkage but not in structural and residual shrinkage, where the water losses exceeds volume decrease.

Soil structure is changing continuously due to external and internal forces affecting consequently soil porosity and its functions. In order to describe the hydraulic behaviour of structured and disturbed soils with different compaction level, the objectives of this work were to determine: (1) the effect of bulk density on the water retention curve, (2) soil shrinkage and (3) its consequences on the hydraulic conductivity.

MATERIALS AND METHODS

Soil material and management

The investigation was conducted on arable soils in a slightly undulating area in Northern Germany. The soil is described as Stagnic Luvisol (FAO, 1998) derived from Loess with two tillage treatments: Conservation (Mulch-M) and Conventional (Plough-P). Mulch defines the treatment when the soil is loosened with a field cultivator to a depth of 8-10 cm, while Plough means ploughing and complete converting down to 30 cm depth. Before 1992 the whole field was uniformly ploughed to 30 cm depth. At the sampling time the soil was cultivated with sugar beet (*Beta vulgaris*). Some physical properties of the studied soils are shown in Table 1.

Table 1. Physical properties of the studied soils

Cuadro 1. Propiedades físicas de los suelos estudiados

Site	Sand [%]	Silt [%]	Clay [%]	d_B [Mg m^{-3}]	TP [%]	Corg [Mg g^{-1}]
P_h	3	80	17	1.2-1.4-1.6	55-47-39	1.4
P_s	3	80	17	1.53	42	1.4
M_h	3	80	17	1.2-1.4-1.6	55-47-39	1.4
M_s	3	80	17	1.47	44	1.4

Ph -homogenized soil samples prepared from Plough; Ps -structured soil samples taken from Plough; Mh -homogenized soil samples prepared from Mulch; Ms-structured soil samples taken from Mulch; d_B-bulk density [Mg m^{-3}]; TP -total porosity [%]; C_{org}-organic carbon content [Mg g^{-1}]

Collection of undisturbed soil samples

The soil sampling took place in November 2003, directly after sugar beet harvesting. Undisturbed soil samples were taken at a depth of 15-19 cm in metal cylinders with 6 replications. Afterwards, the soil samples were put into plastic bags and boxes to avoid evaporation and mechanical disturbances.

Preparation of repacked soil samples by three bulk densities

In addition, from the sieved soil (<2 mm) repacked soil samples with three different bulk densities (d_B) were prepared: 1.2, 1.4 and 1.6 Mg m^{-3} (ten replications for each bulk density prepared with 20% gravimetric water content). To ensure uniform bulk densities, the soil was packed into cylinders at carefully controlled densities by means of a "Load frame" device.

Measurements

In order to determine the effect of bulk density on hydraulic properties four samples were used to measure the water retention curve (WRC) and shrinkage (S), and six to measure the saturated hydraulic conductivity (Ks). First all samples were slowly saturated by capillary rise from beneath. The saturation took at least three days.

Determination of the water retention curve and soil shrinkage

The water retention curve (WRC) was determined at 8 different water suctions. The saturated samples were drained at-10, -20 and -30 hPa on sand tanks. The drainage of the samples at water tensions of -60, -150, -300, -500 hPa occurred on ceramic plates and of -15000 hPa in a pressure chamber. When the samples attained equilibrium with the applied vacuum, the gravimetric water content was determined. At the end, samples were dried in an oven at 105 °C for 16 hours (Hartge and Horn, 1989) to determine and to control the bulk density and volumetric water content. To determine the total porosity, a particle density of 2.63 Mg m^{-3} was used resulting from the dominant quartz.

The shrinkage of the repacked samples was measured during the determination of the WRC. To estimate the vertical shrinkage of the soil their actual height was measured with a calliper at 6 defined points (1 on the middle and 5 on the sides) as was proposed by Peng and Horn (2005).

Determination of the saturated hydraulic conductivity

The saturated hydraulic conductivity (Ks) was measured with a permeameter under instationary conditions. The water flow was measured three times for each soil sample and the arithmetical mean was calculated. The Ks values were log-transformed because of their non-normal distribution (Hartge and Horn, 1989).

Correction of the water retention curve after shrinkage

In order to consider the shrinkage effect on the water retention curve, the vertical shrinkage was used to correct the volumetric water content at each matric potential. Additionally, the structural changes caused by shrinkage were expressed by differences in water content ($d\theta$) with and without consideration of shrinkage, in relation to the volumetric water content at saturation as follows:

$$d\theta = \frac{\theta_{rs} - \theta_{dh}}{\theta_s} \cdot 100 \qquad (1)$$

where θ_{rs} means the volumetric water content of rigid soil [vol%], θ_{dh} is the volumetric water content corrected by shrinkage [vol%] and θ_s is the volumetric water content at saturation [vol%].

At the used water tensions (till -500 hPa) horizontal cracks were not clearly observed in the investigated soils. Additionally, regarding the complicated and irregular geometry of soil cracks, the quantitative and feasible measurement of horizontal shrinkage is more difficult as of the vertical (Peng *et al.*, 2006). Therefore, our investigations were concentrated only on the vertical changes. Such restriction can be justified by the initial dominance of vertical cracks during shrinkage, as it is described in Hartge and Horn (1999).

In order to show the effect of the bulk density and soil shrinkage on the water movement under unsaturated conditions, the hydraulic conductivity as function of the water tension was estimated using the equation (2) proposed by van Genuchten (1980), with and without consideration of the soil deformation as follows:

$$k/\psi = Ks \cdot \frac{\left[-(\alpha \cdot h)^{n-1} \cdot \left(1+(\alpha \cdot h)^{n}\right)^{-m}\right]^{2}}{\left[1+(\alpha \cdot h)^{n}\right]^{m/2}} \quad (2)$$

where k/ψ means the unsaturated hydraulic conductivity [cm s^{-1}], h is the water pressure [hPa], Ks is the saturated hydraulic conductivity [cm s^{-1}] and α, n, m are the van Genuchten parameter of the WRC [-].

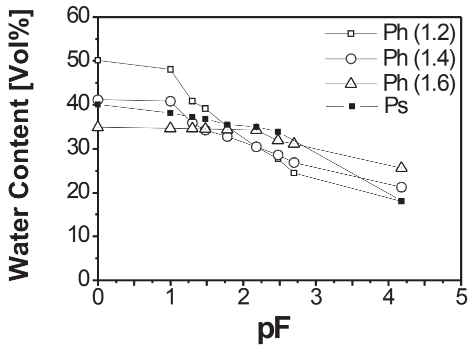
Statistical analysis

Averages for each soil horizon were calculated. In order to proof the effect of bulk density and structure formation on pore-size distribution and Ks, statistical analysis was performed by analysis of variance ($p \leq 0.05$). The differences of means were assessed by the Tukey-Test ($p \leq 0.05$).

RESULTS

Effect of the bulk density on the water retention curve and soil shrinkage

The development of the WRC depends on the soil density as well as on soil structure (Fig. 1). As expected, the saturated water content (θs) decreases with increasing bulk density (Tab. 2). The development of the WRC for the structured samples (Ps and Ms) differs from that of the homogenized material (Ph and Mh), even if they have a nearly similar water content at saturation. It is noticeable that the undisturbed soil samples (both for P and M) start to loose water at higher pF-values (pF 1,78) than the disturbed ones. Those differences can be seen especially in the amount of medium pores (MP).



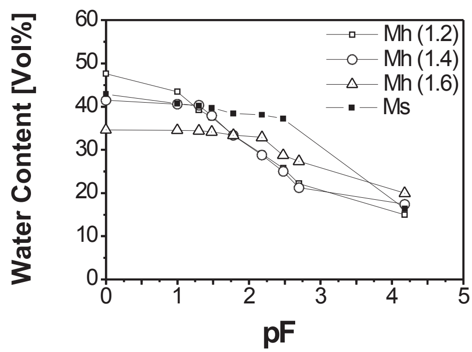


Figure 1. Water retention curves as a function of the bulk density for repacked (Ph, Mh) and undisturbed (Ps, Ms) soil samples

Figura 1. Curvas de retención de agua en función de la densidad aparente para muestras ensambladas (Ph, Mh) y no disturbadas (Ps, Ms) de suelo

Table 2. Pore size distribution (wCP: >50 µm, nCP: 50-10 µm, MP: 10-0,2 µm, FP: >0,2 µm) and saturated hydraulic conductivity (Ks) as function of the bulk density (d_B)

Cuadro 2. Distribución del tamaño de los poros (wCP: >50 µm, nCP: 50-10 µm, MP: 10-0,2 µm, FP: >0,2 µm) y conductividad hidráulica saturada (Ks) en función de la densidad aparente

Treatment	d_B	θs	Pore size distribution [vol%]				K_S
	[Mg m^{-3}]	[vol%]	wCP	nCP	MP	FP	[cm s^{-1}]
Ph(1.2)	1.18a	50.13c	15.07c	7.34d	9.68b	18.03a	-2.16 ± 0.05a
Ph(1.4)	1.39b	41.16b	8.37b	4.21c	7.33a	21.23b	-3.21 ± 0.07b
Ph(1.6)	1.62d	34.90a	0.51a	2.53b	6.26a	25.28c	-5.03 ± 0.29c
Ps	1.53c	n.d.	6.38b	1.26a	16.06c	18.12a	-3.18 ± 0.12b
Mh(1.2)	1.21a	47.65c	14.28c	7.64c	10.75ab	14.98a	-3.62 ± 0.08a
Mh(1.4)	1.42b	41.45b	8.08b	8.34c	7.63a	17.39ab	-4.41 ± 0.13b
Mh(1.6)	1.63c	34.60a	1.22a	4.61b	8.83a	19.93b	-5.12 ± 0.17c
Ms	1.47b	n.d.	5.64b	1.17a	20.77c	16.44a	-3.64 ± 0.32a

In the same treatment, different letters indicates significant differences (Tukey test, $p \leq 0.05$). Ph -homogenized soil samples prepared from Plough; Ps -structured soil samples taken from Plough; Mh -homogenized soil samples prepared from Mulch; Ms-structured soil samples taken from Mulch; n.d. -not determined; ± - standard error

The shrinkage curves show the relation between water content and soil volume changes (Fig. 2). Generally, the void ratio (e) and the moisture ratio (ϑ) at saturation decrease with increasing d_B. Additionally, with increasing d_B the shrinkage curves become shorter and smoother. The residual shrinkage predominates in all investigated samples, i.e. volume decrease is lower than water losses, which can be explained by high bulk density and the used water tension (till -500 hPa).

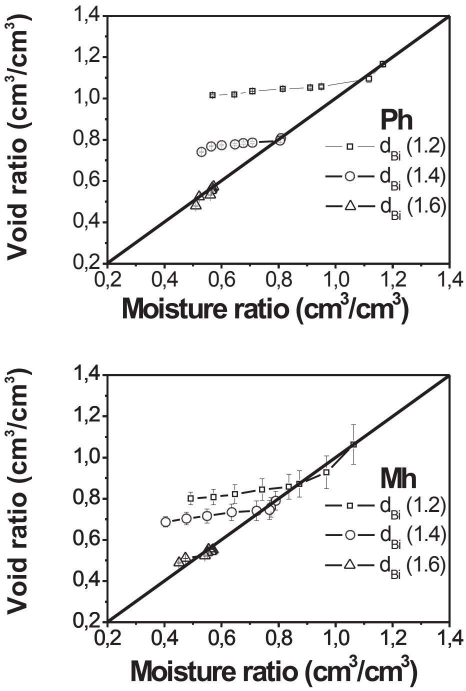


Figure 2. Shrinkage curves of homogenized repacked material prepared from Plough (Ph) and Mulch (Mh). Bars indicate ± 1 standard error

Figura 2. Curvas de contracción del material ensamblado preparado a partir de Plough (Ph) y Mulch (Mh). Las barras indican ± 1 error estándar

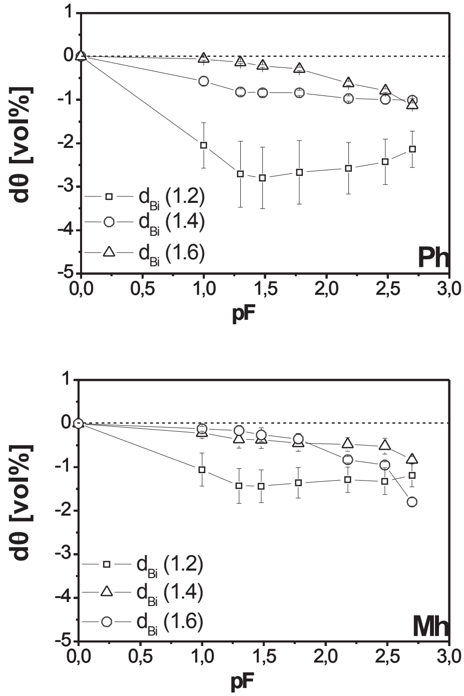


Figure 3. Relative water content differences as a function of the bulk density for repacked soil samples Plough (Ph) and Mulch (Mh). Bars indicate ± 1 standard error

Figura 3. Diferencias relativas en el contenido de agua en función de la densidad aparente para muestras ensambladas a partir de Plough (Ph) y Mulch (Mh). Las barras indican ± 1 error estándar

Although the soil does not present a great shrinkage at the applied water tensions (Fig. 2) some structural changes due to water menisci formation take place. These changes can be evaluated through the relative water content difference (dθ), understood as the difference between the volumetric water content with and without consideration of the shrinkage in relation to the volumetric water content at saturation (Fig. 3). The dashed line represents the situation for the soil assumed as a rigid body, when no changes in the volumetric water content due to shrinkage take place. As the bulk density decreases, a greater deviation of dθ from the dashed line is observed (it becomes more negative) showing that structural changes due to shrinkage become larger. By the lower d_B, the greater deviation of dθ occurs near saturation (till -20 hPa), showing the greater error in the determination of the volumetric water content.

Effect of the bulk density on the hydraulic conductivity

The saturated hydraulic conductivity decreases with increasing bulk density as a response of the smaller volume of coarse pores in the disturbed samples (Table 2).

Ks for Ps and Ph (1.4) do not present statistically significant differences, but Ps has a greater bulk density, which normally coincides with a smaller Ks value. The same values for Ks can be explained by the higher continuity between soil aggregates of the undisturbed pore system at a given bulk density. The undisturbed samples collected from Mulch (Ms) present the same d_B and wCP as shown for Mh (1.4). However, Ks of Ms is significant higher than Mh (1.4), showing the pore-continuity effect of the undisturbed material. In fact, Ms is comparable in Ks with Mh (1.2) even considering the higher d_B of Ms. As the soil drains, k/ψ curve decrease (Fig. 4). However, the intensity of these changes differs depending on the bulk density and pore-size distribution. Differences in k/ψ observed in Ph at pF=3.0 reach almost one order of magnitude depending on d_B, while for Mh this situation was not observed as a result of the faster decrease of k/ at d_B=1.4 than at 1.2 Mg m^{-3}.

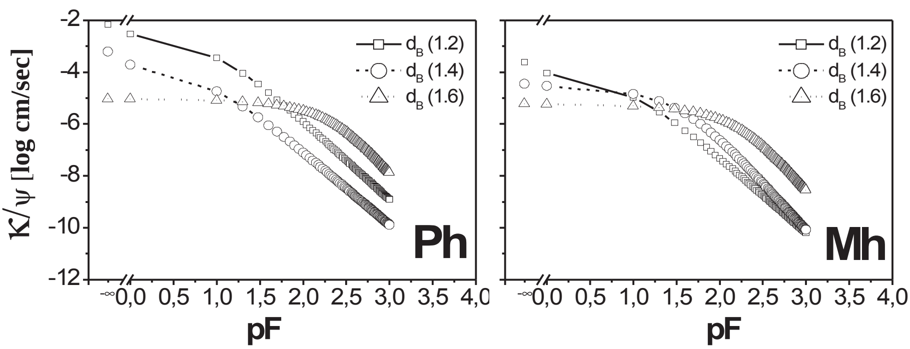


Figure 4. Simulated unsaturated hydraulic conductivity (k/ψ) for three bulk densities by repacked soil samples for Plough (Ph) and Mulch (Mh)

Figura 4. Conductividad hidráulica no saturada simulada (k/ψ) para tres densidades aparentes del suelo ensamblado a partir de Plough (Ph) y Mulch (Mh)

If the volumetric water content is corrected by soil shrinkage, the estimated values of unsaturated hydraulic conductivity increase (Fig. 5). Thus it can be seen that if the soil does not behave as a rigid body, errors in the estimation of the volumetric water content can be made, even in the residual shrinkage range. These discrepancies increase with decreasing bulk density (Fig. 3) and have consequences on the estimation of the unsaturated hydraulic conductivity (Fig. 5).

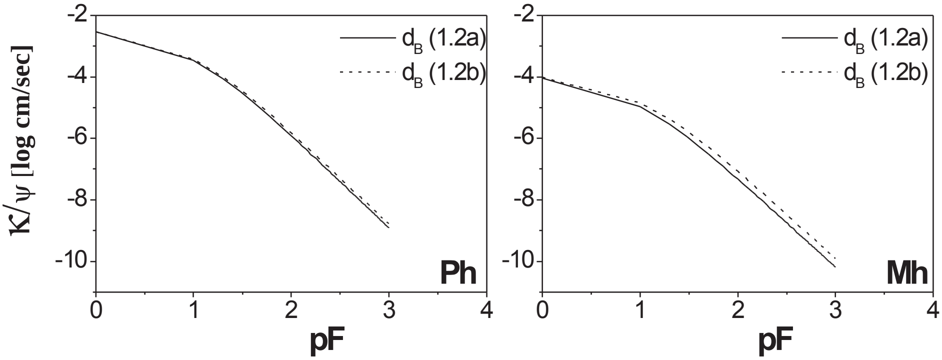


Figure 5. Effect of the soil shrinkage on the unsaturated hydraulic conductivity (a: modeled k/ψ without consideration of shrinkage, b: k/ψ with consideration of shrinkage)

Figura 5. Efecto de la contracción del suelo sobre la conductividad hidráulica no saturada (a: k/ψ sin considerar la contracción, b: k/ψ considerando la contracción)

DISCUSSION

Effect of soil structure on hydraulic properties

Since the soil texture between undisturbed and disturbed samples is identical, differences in the relation between pore volume and pore function are related to the bulk density and soil structure formation. The differences between pore size distributions (or WRCs) of homogenized (repacked) and undisturbed samples are the consequence of soil aggregation. If repacked and undisturbed soil samples collected in Mulch are compared, differences in the WRC at the same d_B were assessed. Remarkable is the higher amount of medium pores in e.g. Ms than in Mh(1.4) which dominates in the conservation tillage persisting over longer periods. This differences tend to decrease (but are in some cases still significant) with increasing drainage, showing the increasing effect of textural pores. This latter effect was confirmed by measurements made by Tuli *et al.* (2005). Disturbed soil samples were only once wetted and dried and, consequently no real aggregation occurs. On the other hand, the structure of the undisturbed soil is a consequence of soil management and successive swelling-shrinkage processes. As Horn and Smucker (2005) suggested, the aggregate formation and strength depend on swelling and shrinking process and on biological activity and kinds of organic exudates as well as on the intensity, number and time of swelling and drying events. The greater differences observed between Mh and Ms are probably related to the conservation of soil structure avoiding the aggregate destruction. This implies, that the pore continuity under Mulch is not interrupted allowing a more intensive water transport. This can be confirmed by investigations made by Buczko *et al.* (2006), who observed higher hydraulically active macropores and higher macropore connectivity under conservation than conventional tillage treatment. Lower macropore connectivity in cultivated soils were amongst others described by Bodhinayake and Si (2004).

Tuli *et al.* (2005) investigated and compared hydraulic properties of undisturbed and disturbed (repacked) soil samples. With respect to the WRC, they found out that repacked soil samples present higher air-entry pressure values than the undisturbed ones, showing the lack of macropores in the disturbed samples. In our results, the volume of macropores (wCP) is the same for Ms and Mh (1.4) but higher for Ps than Ph (1.6). They measured also the air and water permeability. For both investigated properties, undisturbed soil samples showed higher values. This illustrates the contribution of more continuous macropores to water and air permeability for the undisturbed samples. In the same direction, Blackwell *et al.* (1986) mentioned that differences in permeability data between disturbed and undisturbed samples are mostly governed by soil structure and macroporosity. Generally, the amount of macropores, are responsible of the permeability of soil to water near saturation (Iversen *et al.*, 2001). However, the continuity of these pores can not be neglected. The greater Ks for the undisturbed soil in M (Ms>Mh (1.4)) is influenced by the pore continuity reached during the aggregate formation, which does not take place in the disturbed material.

An increasing bulk density in the homogenized material implies a decrease of coarse pores and an increase in middle and fine pores. It is well known that this behaviour induces changes on hydraulic conductivity as assessed in structured soil by Ankeny *et al.* (1990), Fuentes *et al.* (2004), Horn and Smucker (2005). This phenomenon appears as a result of the reduction of structural pores (the large pores are reduced at first, as mentioned by Richard *et al.*, 2001) and the destruction of pore continuity developed during aggregate formation. Saturated hydraulic conductivity for soils with different amount of macropores (and pore continuity) was also described by Cameira et al. (2003), Fuentes *et al.* (2004) and Buczko *et al.* (2006). They investigated different soil types under two tillage treatments and assessed lower Ks for conventional than conservation treatment responding to a lower soil aggregation (Six et al., 1999; Pinheiro *et al.*, 2004) and higher disturbance of macropores continuity (Osunbitana *et al.*, 2005). Improvement of pore continuity with increase of macropores was also noticed by Currie (1965) who investigated gas transport in highly developed natural aggregated soils. He pointed out that preferentially gas transport in soil profile occurs through the inter-aggregate pore system (more continuous than zones of aggregated or crumb pores) formed by macropores, being reduced in compacted soils. The same trends were also described by Fujikawa and Miyazaki (2005) for alluvial soils.

Effect of bulk density on shrinkage

Regarding the importance of water for all processes in soil, their hydraulic properties are often investigated and well understood if we assume a rigid pore system. Soils, however, are no rigid bodies which results in changes in their properties as a result of internal and external forces. If we want to understand the effect of shrinkage on hydraulic properties, measurements on disturbed and repacked soil samples can give a good insight in the effect of non rigidity on hydraulic functions. However, the possibility of extrapolation to in situ conditions can be rather restricted because of the exclusion of water uptake effects through roots on soil structure formation but at least it represents the seedbed conditions. Peng and Horn (2005) mentioned that soil homogenization due to repeat ploughing always results in an altered shrinkage pattern in comparison with the identical soil without any intermediate homogenization. The ability of soil to shrink decreases exponential with increasing d_B, as far as the soil particle/aggregates get closer. Horn *et al.* (1991) showed that at a given dehydration stresses, less structured soils were easy to deform. If soils are compacted the amount of contact points between particles and soil strength increases (Hartge and Horn, 1999), which results in a reduced mobility of particles to rearrange (Hartge, 2000). Consequently, a more negative suction is needed to regain structural changes. As the soil drains the water menisci formation induce shrinkage affecting the volume of medium and fine pores (Peng and Horn, 2007) and the volumetric water content (Figure 3). The later is underestimated and consequently the simulation of k/ψ with the van Genuchten is underrated as well. The underestimation depends on the rigidity of the pore system (determined by the cohesion between particles and the angle of the internal friction) and the applied water suction (or intensity of drainage).

CONCLUSIONS

1. Structural changes affect the porous media in their volume and function. These changes get larger with decreasing bulk density.
2. Structural changes take place due to internal (shrinkage) and external forces (compaction) and affect the hydraulic behaviour of these soils.
3. The aggregation of the soil is more intense in undisturbed soil samples due to successive wetting and drying cycles prefer the creation of new pores.
4. The structural changes due to water loss can be represented by dθ Without consideration of dθ the values of k/ψ can be underestimated.

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